Order Number 9325172

Forecasting catches of Pacific salmon in commercial fisheries of southeast Alaska

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University of Alaska Fairbanks, 1992

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FORECASTING CATCHES OF PACIFIC SALMON IN COMMERCIAL FISHERIES OF SOUTHEAST ALASKA

A

THESIS

Presented to the Faculty

of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

By

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Juneau, Alaska

December 1992

FORECASTING CATCHES OF PACIFIC SALMON IN COMMERCIAL FISHERIES OF SOUTHEAST ALASKA

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THESIS ABSTRACT

Data collections since 1911 and statistical methods from time series analysis are employed to forecast catches of pink, chum, coho, and sockeye salmon in Southeast Alaska. Knowledge of the spatial and temporal domains favored by Pacific salmon originating in Southeast Alaska is summarized to provide a basis for estimating environmental variation experienced by each species.

Catches in northern, southern, and all of Southeast Alaska are forecast with univariate ARIMA, transfer function-noise (TFN), and vector ARMA models. Univariate models for catch in numbers and catch in weight yielded similar results for each species.

Air and sea surface temperatures, freshwater discharge, and coastal upwelling enter TFN models for several species and areas. Environmental variables allow TFN models to explain a small amount of variation in the catches (average of 19%) above that explained by univariate models. Forecasts for most, but not all, species and areas are improved (average of 16%) by including environmental data in TFN models.

Stock-recruit models with a parameter for density dependent mortality provide the best forecasts of pink salmon catch and are recommended for future forecasts. Winter air and sea surface temperatures enter stock-recruit models for pink salmon, and forecasts of catch and recruitment in northern and southern Southeast Alaska tend to oppose each other and cancel (1981-1985), which suggests that the salmon are caught in areas other than where they originated. Mean absolute percentage error (MAPE) for forecasts of pink salmon catch from stock-recruit models in Southeast Alaska, based on data for 1981-1990, is estimated at 49%, with first, second, and third quartiles of 10%, 23%, and 83%, respectively.

Catches of Pacific salmon in Southeast Alaska are significantly correlated and are forecast jointly with good accuracy by vector ARMA models, except when effects believed to result from density dependent mortality are present in the data. Correlations indicate that coho salmon smolts might prey on young pink salmon. Also, recruitment of pink salmon in Southeast Alaska and British Columbia is correlated; regional environmental influences might thus affect catches in both areas. In Southeast Alaska, MAPE for forecasting coho and sockeye salmon catch with time series analysis is about 20%, and about 30% for chum salmon.

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ACKNOWLEDGMENTS

Dr. Philip R. Mundy proposed development of time series models to forecast salmon catches in the major net fisheries of Alaska. The proposal was sponsored by the Alaska Sea Grant College Program in 1986, supported by NOAA, Office of Sea Grant and Extramural Programs, and by the University of Alaska Fairbanks. Dr. Terrance J. Quinn II assumed the project when Dr. Mundy left the University of Alaska to become Chief Fisheries Scientist for the Alaska Department of Fish and Game (ADF&G).

I thank Dr. Ole A. Mathisen, Dr. Mundy, and Dr. Quinn for making it possible to enter the Ph.D. program at the University of Alaska, and to work in Juneau, Alaska. Dr. Amir D. Aczel supplied the fundamentals and enthusiasm for time series analysis.

I am grateful to Dr. Terrance Quinn (Chair), Dr. Vera Alexander (co-Chair), Dr. Mundy, Dr. Thomas C. Royer, and Dr. Aczel for serving on my advisory committee. Each member of my committee provided exceptional support when it was needed, and freedom to conduct this work at the University of Alaska.

I thank Ron K. Dearborn, Director of the Alaska Sea Grant College Program, for attention to and support of the project, and the many educational opportunities provided to me by Alaska Sea Grant. I am also grateful to employees of the ADF&G Division of Sport Fish for patience and support during the final stages of the project.

The University of Alaska provided financial assistance to lease computer software for the study through the Clarence L. Anderson Scholarship Fund. Richard Meeker and Michael Ciri helped make mainframe-computing in Juneau a pleasant, productive task.

David Reilly (Automatic Forecasting Systems) and William Lattyak (Scientific Computing Associates) provided help with time series analysis and statistical computing. Faculty at the Juneau Center for Fisheries and Ocean Sciences, Scott L. Marshall (ADF&G), and Karl Hofmeister, Leon D. Shaul, J. Douglas Jones, and others at the Alaska Department of Fish and Game provided discussion, ideas, and encouragements that improved the thesis. Alma Seward provided editorial advice and assisted with graphics.

Terry Quinn was a great teacher, advisor, and friend during this project. Terry's cheerful support and guidance during the project are greatly appreciated. Finally, the encouragement from my parents Paul and Francis Marshall, my brothers Scott and Tim, friends, and Deborah Craig are gratefully acknowledged.

CHAPTER 1
INTRODUCTION

Southeast Alaska (Figure 1.1) covers about 78,000 km^2 and contains over 2,500 streams which support anadromous Pacific salmon (Jones and Dangel 1986). The Alaska Department of Fish and Game (ADF&G) publishes annual forecasts of the commercial catches of pink salmon (*Oncorhynchus gorbuscha*) in southern and northern Southeast Alaska, as well as commercial catches of sockeye salmon (*O. nerka*), chinook salmon (*O. tshawytscha*), chum salmon (*O. keta*), and coho salmon (*O. kisutch*) in a dozen or so other fisheries in Alaska. Informal harvest projections for all salmon runs in Alaska are also prepared by local ADF&G managers (Geiger and Savikko 1991).

Tremendous fluctuations occur in the numbers of salmon landed annually in Alaskan fisheries, and both relative and absolute error in forecasts of catch and return (i.e., catch plus escapement) to important fisheries are sometimes high. Forecast error for pink salmon catch in southern Southeast Alaska, for example, ranged from -73% to +68% between 1981 and 1985. The average annual ex-vessel value (gross receipts to fisherman) of this single fishery (1981-1985) was about 26 millon (constant 1990) dollars, and significant economic loss reportedly occurs because these catches cannot be forecast precisely.

This research was initiated to determine if long-term data collections and time series analysis could improve the forecasting of salmon catches in Alaska. A univariate analysis of pink, chum, sockeye, and coho salmon catches in Bristol Bay, Kodiak, Cook Inlet, Prince William Sound, and Southeast Alaska suggested dissimilar models for each species (except pink salmon) across fishing regions, and dissimilar models for catches of different species within fishing areas (Marshall and Quinn 1987). This analysis also demonstrated that it was impractical to forecast each of these series with attention to detail and with predictor variables.

Thus, comprehensive analysis of pink, chum, sockeye, and coho salmon catches in Southeast Alaska was begun (Quinn and Marshall 1989). Catches of chinook salmon in Southeast Alaska are regulated by multinational quotas, and hence are not considered. This dissertation includes many extensions to the analysis of Quinn and Marshall (1989) and presents a more complete analysis of forecasting salmon catches in Southeast Alaska.

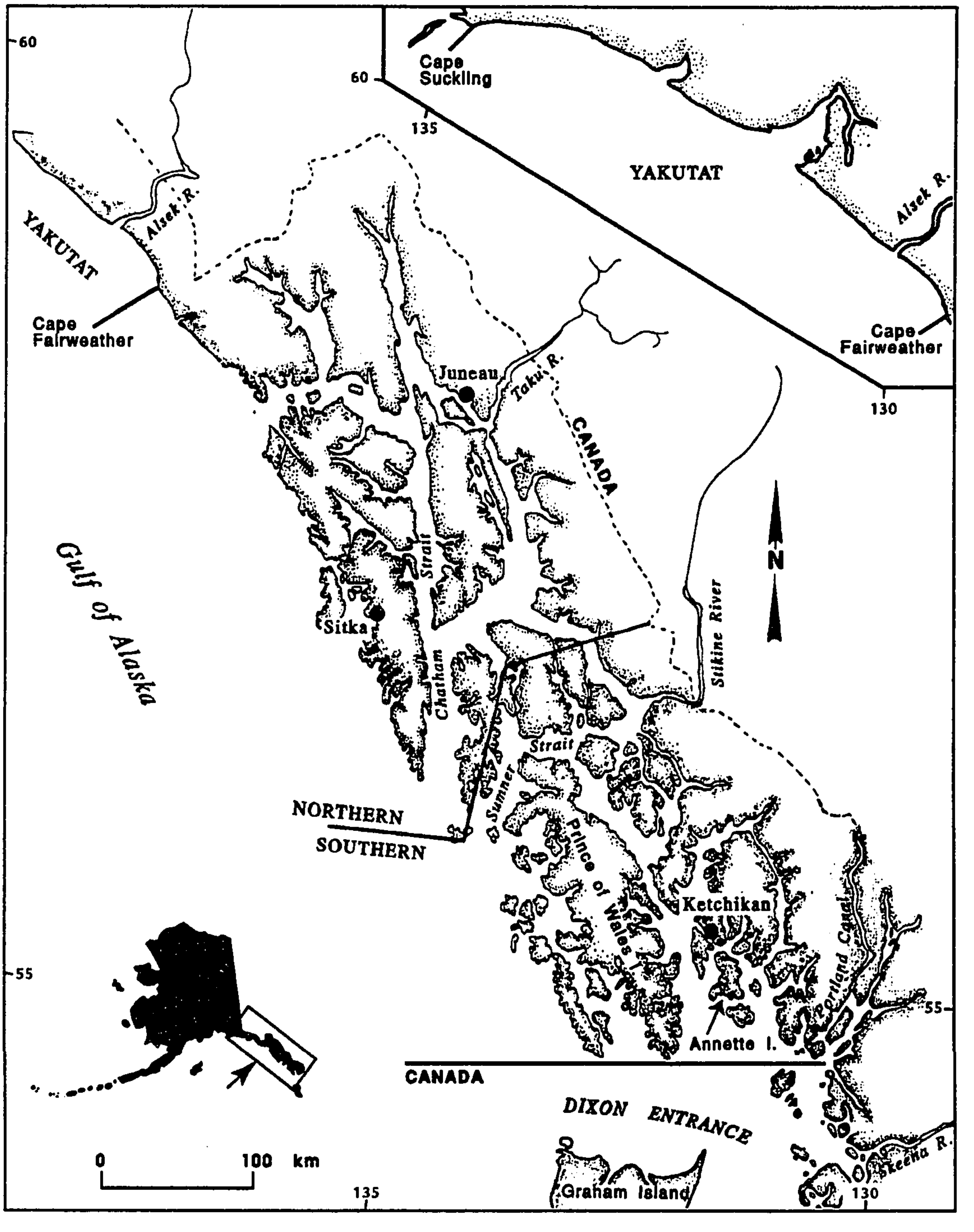


Figure 1.1. Map of Southeast Alaska showing Alaska Department of Fish and Game management areas (northern Southeast Alaska, southern Southeast Alaska, and Yakutat) and selected locations.

Catches and returns of pink salmon to Southeast Alaska are notoriously difficult to forecast (Geiger and Savikko 1991). Since projections (not formal forecasts) of chum, coho, and sockeye salmon catches in Southeast Alaska are made, the results in this thesis for these species might seem less important than results for pink salmon. However, considerable effort is devoted to each species, and a theme in this work is to compare and contrast results between species and regions in Southeast Alaska, in order to produce a more robust application.

The research had several objectives, including: compiling the catch data; compiling long-term environmental data that was spatially and temporally relevant to important life history events; describing varied statistical methodologies ("time series analyses") for forecasting catches; developing forecast models for each series in Southeast Alaska; and demonstrating the results by forecasting catch for an important Alaskan salmon fishery. The dissertation is developed in chapters, which stand alone to the extent practically possible. Chapter 2 describes relevant information on the salmon and salmon fisheries of Southeast Alaska. The statistical history of the catch data for Southeast Alaska, and the series for analysis are also described in this chapter. A synthesis of information regarding the spatial and temporal aspects of the life history of Pacific salmon is also outlined, so that hypotheses about the interactions between salmon and their environment can be translated into a manageable array of time series to be considered in the analysis. Average weights of salmon were also estimated, so that an index of growth is available.

Environmental data with time scales of days to years, and space scales ranging from regions within Southeast Alaska to broad reaches of the northeastern Gulf of Alaska are described in Chapter 3. Spatial and temporal scales are defined first by the catch data, that were summarized by management areas in Southeast Alaska, then by life history parameters that define the seasonal periods of residence in fresh water, early marine, and high seas environments.

The notation and methodology of univariate time series analyses is described in Chapter 4, and the application of these statistical methods to the data for Southeast Alaska is described in Chapter 5. Comparisons between environment and the catch, average weight, and the logarithm of survival for pink salmon are made in Chapter 6, in order to broaden the scope and supplement the time series analyses.

Methods for modeling one dependent variable using its own past history and one or more exogenous (environmental) series are described in Chapter 7. These techniques (transfer function-noise modeling) are applied to the catch and environmental data for Southeast Alaska in Chapter 8. Because catches of the different species may be significantly related, a methodology for constructing models of several dependent series (vector ARMA modeling) is described in Chapter 9. An investigation which considers the catches of pink, chum, coho, and sockeye salmon in Southeast Alaska as a single related system, including environmental data, is presented in Chapter 10.

Chapter 11 demonstrates forecasting models for pink salmon in Southeast Alaska. Forecasts from six different models are compared to permit selection of the best model for subsequent forecasting. The results are discussed in the context of the successes and failures in earlier chapters, and a summary of conclusions and recommendations for forecasting catches in Southeast Alaska is provided.

About the time I began this project, I had a discussion with Dr. Ole Mathisen (SFOS, UAF) in which he emphasized the importance of economics and politics in fisheries. A rich and colorful history of the fisheries of Alaska is recorded, and the fisheries of Southeast are prominent in these reports, many of which are referenced below. However, long series of statistically relevant information, such as labor costs and standardized fishing effort, were (or could) not be easily constructed from the historic data. Thus, a great deal of historic information is not incorporated in this dissertation.

Even before 1930, changing economic and environmental conditions, and overfishing were thought to be observable in time series of Alaskan salmon catches (Rich and Ball 1928, 1933), and varied trends in the catches in different fisheries were clearly evident. After many years of expansion, high catches and the great depression, expenditures for fisheries management in Alaska declined steadily (Royce 1962). In the 1940's, salmon catches across Alaska dropped steadily.

Funding for management and research of Alaska salmon increased sharply in 1949 and in 1957 (Royce 1962). Many factors may have contributed to the poor catches recorded in the 1950's and 1960's, and overfishing has been cited as a possible factor (Cooley 1961; Pennoyer 1979). High sea interceptions, which increased as United States and foreign fisherman expanded their ranges in the 1950's (Jackson and Royce 1986) could be another factor. However, there is little evidence for foreign interceptions of large numbers of salmon bound for Southeast Alaska (Harris 1988). Finally, salmon catches across Alaska increased sharply in the late 1970's and early 1980's, and again, management is quoted as being influential (Royce 1989).

It should be emphasized that other quantitative data potentially relevant to this study may exist. For example, consideration could be given to data related to the global environment (e.g., solar activity, El-Niño, ice cover, etc.) and to data associated with particular stocks of salmon in Southeast Alaska (e.g., Alexandersdottir 1987). Subsequent analysis that considers these and other variables will further advance the science and art of forecasting catches of Pacific salmon.

CHAPTER 2
CATCH, ESCAPEMENT, AND LIFE HISTORY

2.1 Overview of Historical Catch and Escapement Data

Catch statistics for Southeast Alaska are available since 1878 when the first canneries were constructed at Redoubt (Old Sitka) and at Klawock (Moser 1899). In 1903, the U.S. Bureau of Fisheries (USBF) was established to manage commercial fisheries in Alaska. The USBF published an annual statistical summary about the commercial fishing industry in Alaska, which was continued by the U.S. Fish and Wildlife Service (USFWS) through 1957 (USBF 1904-1910; USBF 1911-1939; USFWS 1940-1957). Similar (USFWS) statistical reports for 1958 and 1959 fisheries exist as unpublished documents. These reports are collectively referred to as the *Alaska Fisheries and Fur-seal Industries* reports after titles used between 1911 and 1939, and document the catch in numbers and weights of products marketed in each region of Alaska. Since 1906, the number of fish caught are reported for all areas of Southeast Alaska from Portland Canal northwestward to and including Yakutat Bay (Figure 1.1). The weight of products marketed is reported in a consistent format since 1911.

Starting in 1927, estimates of commercial catch biomass landed in Southeast Alaska were reported in the annual synopses *Alaska Fisheries* (USBF 1927-1939; USFWS 1940-1959), but until 1958, the estimates were derived by multiplying numbers of fish landed times a statewide "average" weight thought to be representative for each species. This statewide "average" was usually unchanged from year to year and was used rather arbitrarily to estimate landed biomass from catches in numbers.

In 1949 the Alaska Department of Fisheries was created, and in 1951, a fish ticket and punch card system was established at the Montlake Laboratory in Seattle to compile Alaska's fishery statistics (Simpson 1960). In 1957, the Montlake statistical unit moved to Juneau, Alaska, and in 1958 the first regionally specific average weight estimates for commercial landings were used to convert catch (in numbers) to biomass (pounds). Estimates of catch and biomass landed from 1960 to 1985 are reported in the Alaska Department of Fish and Game (ADF&G) statistical leaflets which are collectively referred to as *Alaska Catch and Production* series (ADF&G 1960-1964, 1965-1985).

Southeast Alaska is divided into three large areas for statistical reporting and management purposes. Southern Southeast Alaska (Figure 1.1) extends from Dixon Entrance northwest to Sumner Strait and the Stikine River (ADF&G districts 101 through 108). Northern Southeast Alaska extends from Sumner Strait northwest to Cape Fairweather (ADF&G districts 109 through 116). Yakutat extends from Cape Fairweather to Cape Suckling (ADF&G districts 118 and 119). Pink salmon runs in these three areas have been regarded as distinct from one another for management, research, and forecasting purposes (Nakatani et al. 1975; Alexandersdottir 1987; Geiger and Savikko 1991). Estimates of the numbers of salmon caught in these areas between 1878 and 1971 have been summarized by Edfelt (1973). Numbers of salmon landed before 1928 were taken (by Edfelt) from Rich and Ball (1933). Numbers landed between 1928 and 1950 were calculated (by Edfelt) from *Alaska Fisheries and Fur-seal Industries* reports of landed catch and the proportion of salmon packed in northern and southern Southeast Alaska. Between 1951 and 1959 the numbers landed are from Simpson (1960), and from 1960 the catches are from the *Alaska Catch and Production* series.

Escapements to major pink and chum salmon streams in Southeast Alaska have been monitored annually by ADF&G since 1959 (Jones and Dangel 1981). The emphasis in these monitoring programs has been to count pink salmon from airplanes, but foot and boat surveys and weirs have also been employed. Indices of pink salmon escapement to Southeast Alaska are obtained by summing the largest counts obtained in individual streams and expanding for the estimated number of unsurveyed streams producing pink salmon. The indices are computed by ADF&G district and have been recalculated as the estimated total number of streams producing pink salmon increased with new information, and standard methods were adopted for each management area. Escapement indices for summer chum salmon runs are constructed using a selected subset of the survey data and no expansions (Jones and Dangel 1986). Similar indices have not been reported for sockeye or coho salmon. Escapements of coho salmon in seven streams for assorted years between 1974 and 1984 are found in Wood and Van Alen (1987). Pella et al. (1988) estimated the total sockeye salmon escapement in southern Southeast Alaska in 1982 and 1983.

2.2 Selection of Series for Catch in Numbers

An electronic file of the estimates of the numbers of salmon landed in commercial fisheries in Yakutat, northern, southern, and Southeast Alaska (southern, northern, Yakutat) management areas between 1878 and 1984 was obtained from ADF&G. These estimates are updated annually, after the compilation by Edfelt (1973). Time series of catch in numbers are derived from these data after various adjustments, discussed below. Estimated catches in 1985 are from an ADF&G computer summary in February 1986.

Commercial salmon fisheries, including those in Southeast Alaska, began as small enterprises, so early catches are not good indicators of salmon abundance. Therefore, an algorithm was defined to choose series of catches minimally affected by the start-up process in each fishery. Each series begins with the year of the first catch on or after 1911 which is closest to half the maximum recorded catch in the series. The year 1911 was selected because after this time estimates of the weights of salmon products marketed in Southeast Alaska were consistently reported.

Miscellaneous salmon catches recorded in Southeast Alaska but not allocated to specific management areas were, for this analysis, allocated to areas in proportion to the known catches in each region in each year. In addition, because catches in Yakutat and northern Southeast for 1928, 1929, 1932, and 1950 were reported together, the contribution to each area was estimated from the relative contributions in each area in neighboring years. Details of the computations can be found in Marshall and Quinn (1987). To limit the number of analyses in this study, I did not separately consider the data for Yakutat, Alaska. The resulting time series are found in Tables A1-A3 and Figures 2.1-2.4.

2.3 Estimation of Catch Biomass

The biomass of pink, chum, coho, and sockeye salmon landed commercially in Southeast Alaska between 1911 and 1957 was estimated from the record of catches and product weights reported in *Alaska Fisheries and Fur-seal Industries* (Marshall and Quinn 1988). The estimates of biomass for the period 1911-1957 were then appended to series of estimates made by the U.S. Fish and Wildlife Service and ADF&G between 1958-1985 (Table A4 and Figures 2.5-2.6). Biomass estimates are for round (undressed) weights. Average weights of salmon in commercial catches of Southeast Alaska were then estimated as the ratio of catch in numbers to catch biomass. Details of the calculations are found in Marshall and Quinn (1988).

2.4 Overview of Life History

Life history information enables relationships between salmon catch or abundance

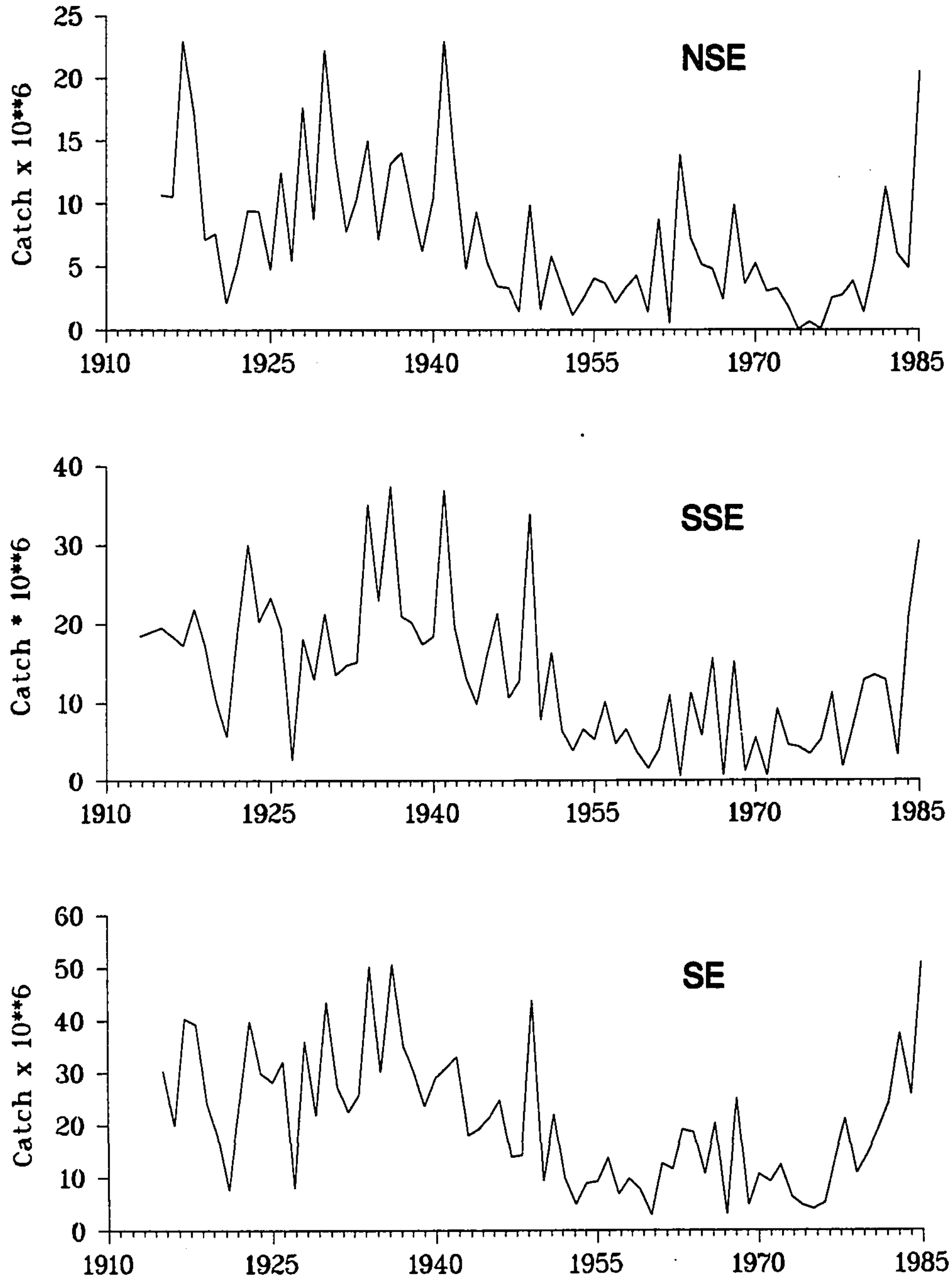


Figure 2.1. Catches of pink salmon in northern (NSE), southern (SSE), and Southeast (SE) Alaska.

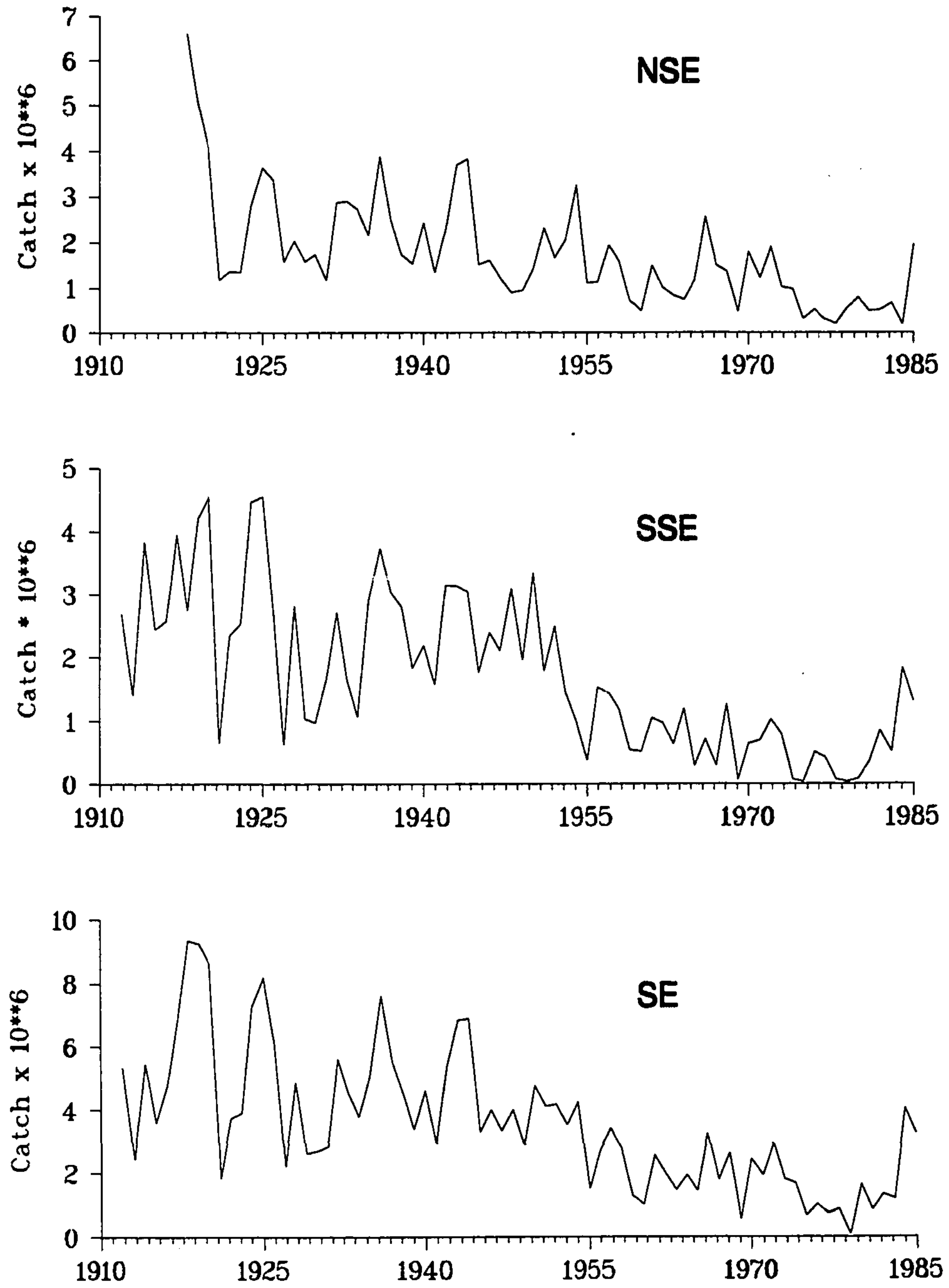


Figure 2.2. Catches of chum salmon in northern (NSE), southern (SSE), and Southeast (SE) Alaska.

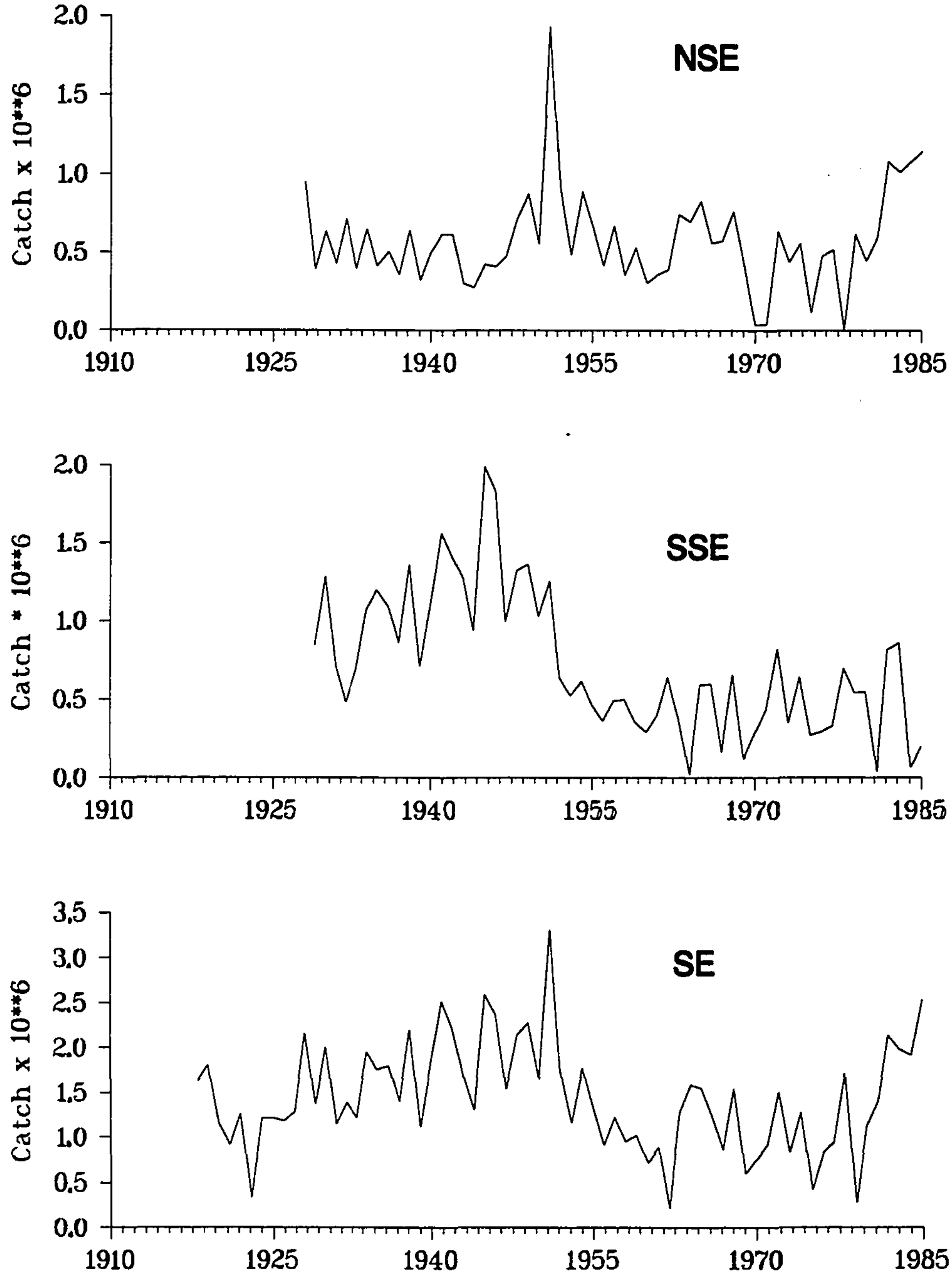


Figure 2.3. Catches of coho salmon in northern (NSE), southern (SSE), and Southeast (SE) Alaska.

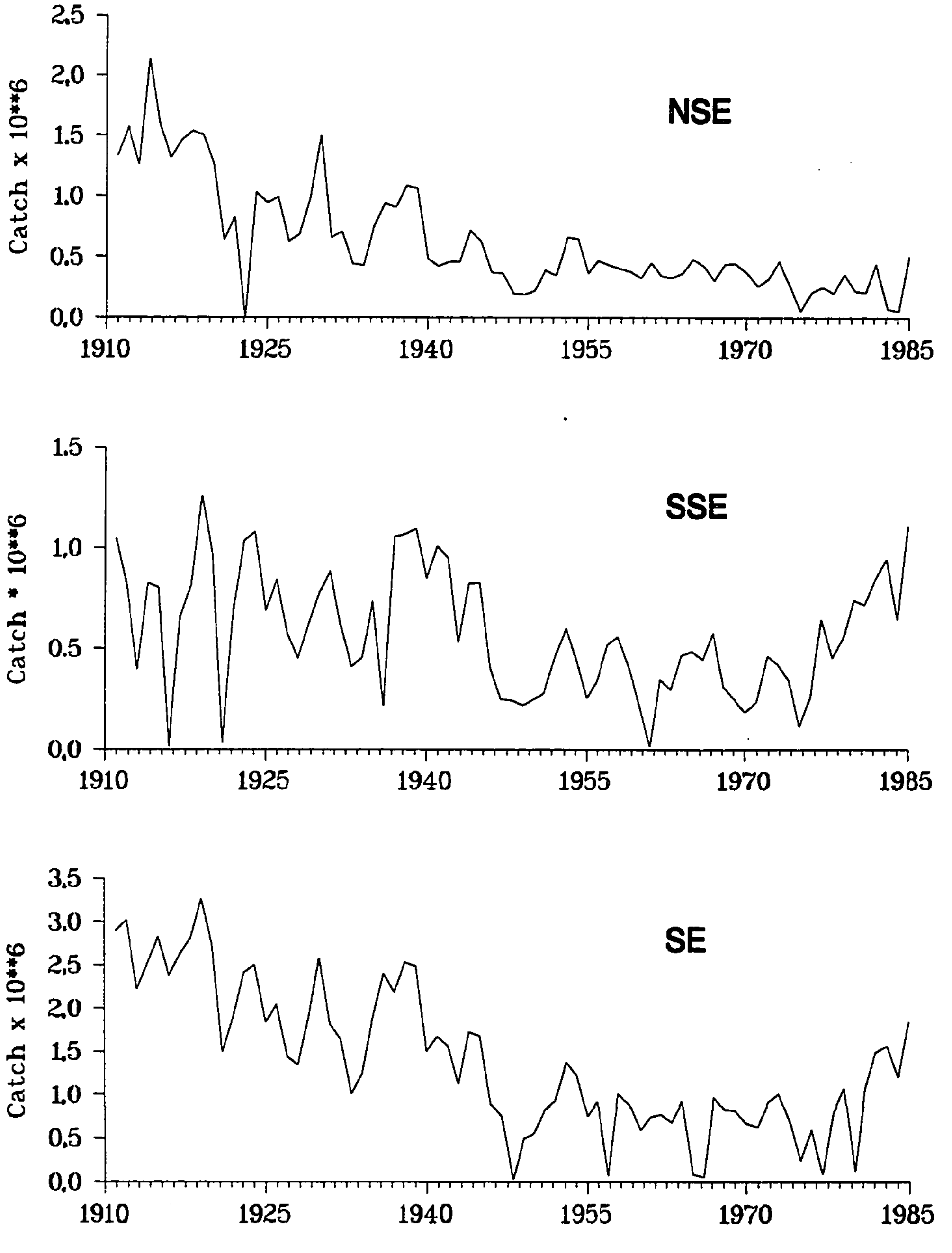
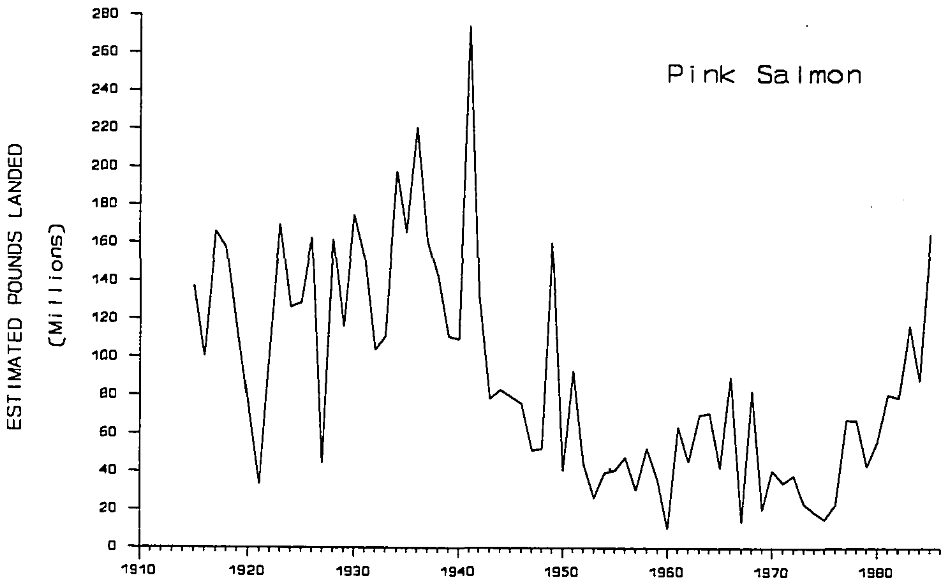


Figure 2.4. Catches of sockeye salmon in northern (NSE), southern (SSE), and Southeast (SE) Alaska.



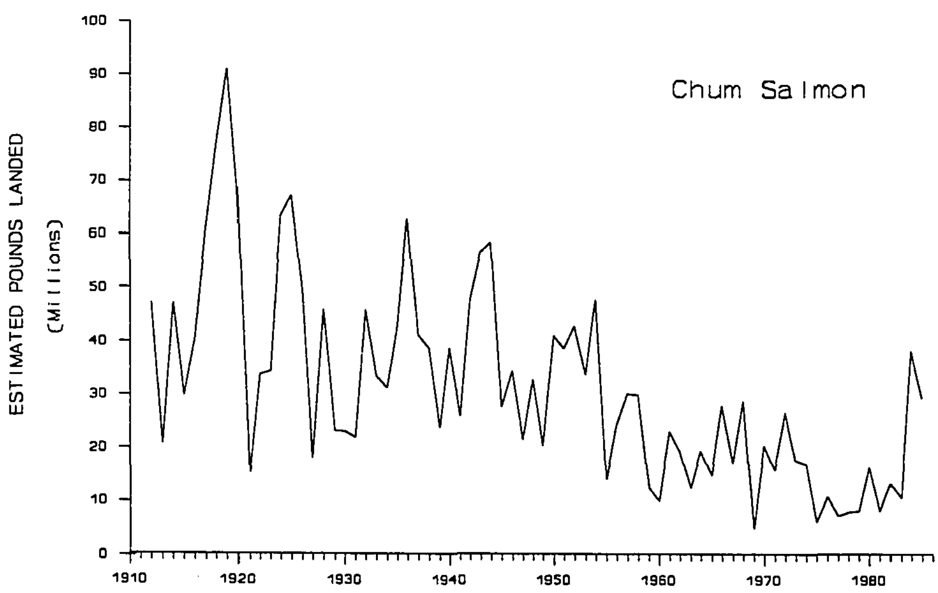


Figure 2.5. Biomass of pink and chum salmon landed in the commercial fisheries of Southeast Alaska.

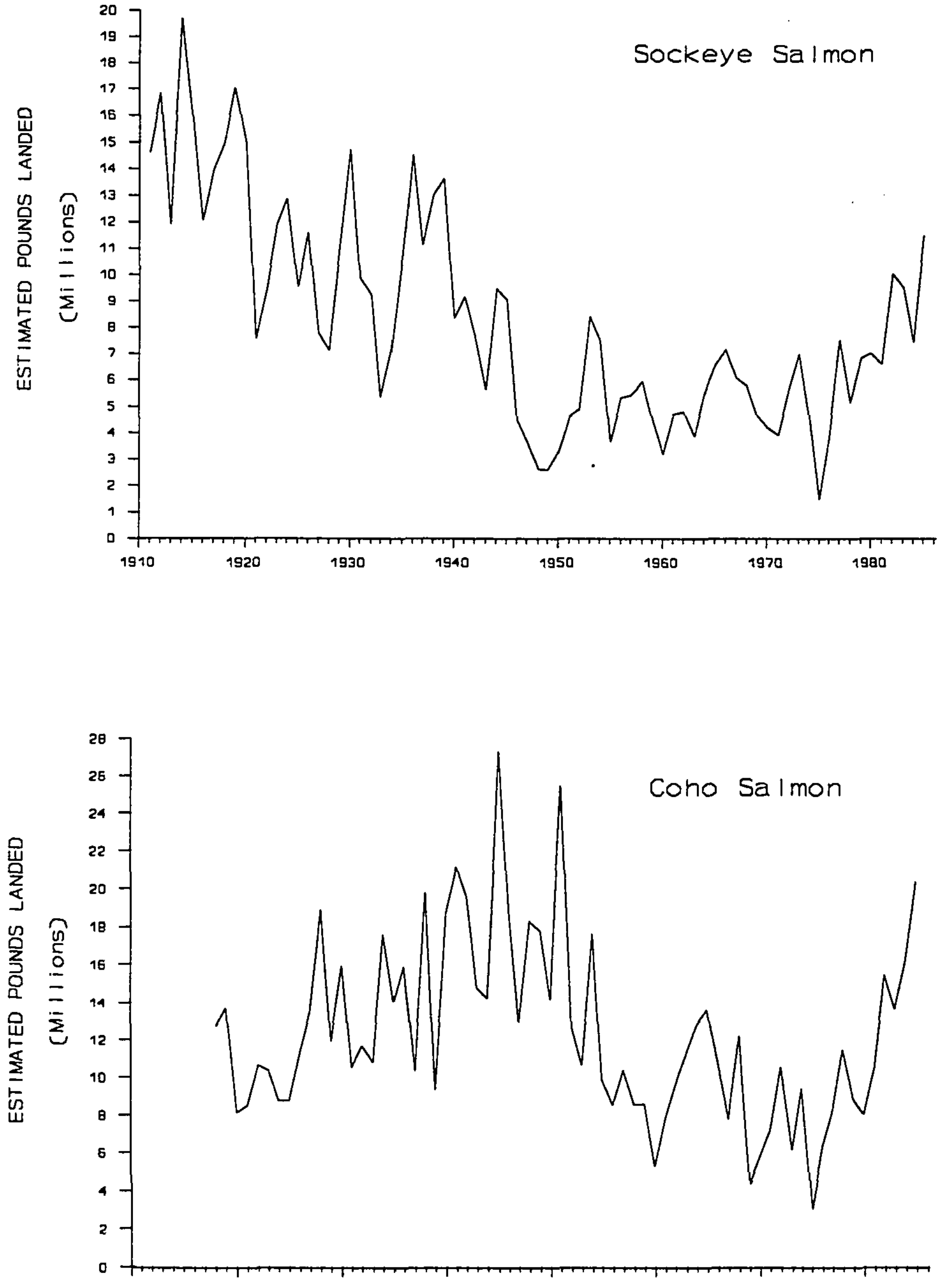


Figure 2.6. Biomass of coho and sockeye salmon landed in the commercial fisheries of Southeast Alaska.

and environmental parameters to be formulated in terms of the spatial distributions of the fish by age and time of year. A brief review of life history-related studies with emphasis on timing of events, spatial distributions, and average ages at maturity are therefore presented. Since a great deal of variation exists in the life histories of Pacific salmon, generalizations were made in order to complete a description involving the time (1911-1985) and space scales of interest in Southeast Alaska.

Pink, chum, sockeye, and coho salmon are all anadromous and have adapted this strategy in different ways. The adaptations can be grossly classified according to utilization of freshwater and marine environments (Table 2.1). Pink and chum salmon leave their native streams during their first year of life; sockeye and coho salmon typically spend at least one year in fresh water. The two groupings can be further divided by utilization of the marine environment; pink and coho salmon spend only one winter at sea while chum and sockeye salmon usually spend two or more winters at sea.

Three time divisions (early, middle, and late) have been used to describe the timing of migrations of adult pink salmon through the commercial fisheries of Southeast Alaska (Sheridan 1962; Martin 1966; Alexandersdottir 1987). Early-run pink salmon generally travel to colder streams of northern Southeast Alaska's inside waters and spawn before August 15. Late-run pink salmon generally travel to warm areas of southern Southeast Alaska and spawn after September 15, while middle-run pink salmon tend to spawn between these two times in central areas of Southeast Alaska. Peak spawning dates probably changed over the years due to time-selective patterns in fishing effort (Alexandersdottir 1987). According to Atkinson et al. (1967), the peak of chum salmon spawning activity occurs in August and September in northern Southeast Alaska and shifts to September and October in southern Southeast Alaska, like that of pink salmon.

The distributions of peak spawning times for coho and sockeye salmon in Southeast Alaska are not well documented. Atkinson et al. (1967) place peak spawning times for coho salmon as similar to pink and chum salmon, and for sockeye salmon in August and September; however, ADF&G biologists whom I queried guessed a later date for the peak of coho salmon spawning (early November). To investigate, I estimated dates for coho and sockeye salmon from compilations of peak escapement counts in 1985 made by foot, boat, and aerial surveys reported in Wood and Van Alen (1987) and McPherson and McGregor (1986). I computed mean dates t as

Table 2.1. Four-way classification of life history strategies of Pacific salmon in Southeast Alaska. A small percentage of precocious chum, coho, and sockeye salmon return to native streams before spending 18 months at sea, and a small percentage of sockeye salmon fry migrate to sea without spending one winter in fresh water.

	Marine residence about 18 months (1 winter at sea)	Marine residence exceeds 2 years (2 or 3 winters)
Juveniles leave fresh water in spring of hatch	pink	chum
Juveniles reside in fresh water at least 1 year after hatch	coho	sockeye

$$\bar{t} = \sum_{i}^{\infty} t_i (c_i/T) \qquad i = 1,2,...$$

where t_i is the Julian date of the observed peak count c made in stream i, and T is the total number of counts made in the surveys. The peak dates for 1985 are September 2 for sockeye salmon and October 8 for coho salmon. Because the surveys are designed to count the salmon before they spawn and die, this method may also underestimate the date of peak spawning. However, August and September seem reasonable for sockeye salmon, while October and November seem reasonable for coho salmon.

In Southeast Alaska, most pink and chum salmon fry emerge from the gravel and begin migrating to salt water in April and May (Martin 1966; Jones et al. 1988). Martin (1966) classifies the timing of juvenile pink salmon downstream migrations into early, middle, and late categories (as for adults), using May 1 and May 15 as the cut points between the three groups. Migrant pink salmon that enter salt water during April generally remain in estuaries until May (Martin 1966). Both species typically remain nearshore for several months before dispersing into the open sea (Martin 1966; Scott and Crossman 1973; Celewycz 1984). Juvenile chum salmon probably remain in low salinity marine waters longer than pink salmon (Healey 1980; Simenstad and Wissmar 1984). Celewycz (1984) recorded peak beach-seine catches of pink and chum salmon fry in the inside waters of northern Southeast Alaska between mid-May and early June of 1981 and 1982. Healey (1980) recorded peak catches-per-set of pink and chum salmon fry in the Gulf Islands region of Georgia Strait in June of 1976. In 1964 and 1965, concentrations of schooling juvenile pink salmon around Southeast Alaska were located, and peak migrations into the Gulf of Alaska were observed during the end of July and the first part of August (Martin 1966).

Coho salmon fry emerge from early March to late July (Scott and Crossman 1973). In Sashin Creek between 1956 and 1968, the emergence of coho salmon fry was usually completed in April and May (Crone and Bond 1976). In Southeast Alaska, coho salmon remain in fresh water for one to four, but typically two, winters (Crone and Bond 1976). Juvenile coho salmon begin migrating to sea from February to June, but most arrive in salt water in late May (Scott and Crossman 1973). In Sashin Creek, peak emigrations of fry and smolts typically occurred between mid-May and mid-June (Crone and Bond 1976). The smolts most likely migrate through estuaries rather quickly (Levings 1984; Simenstad and Wissmar 1984). Seining conducted through June in northern Southeast Alaska showed peak catches of smolts in late June (Celewycz 1984), and Healey (1980) found high catches-per-set in July, August, and September in the Gulf Islands.

Sockeye salmon emerge from April to June (Scott and Crossman 1973). While some fry migrate to salt water shortly after emerging, most migrate to a lake environment, then spend one, two or three winters in fresh water before migrating to sea. Sockeye salmon smolts concentrate near the mouth of the Fraser River in April and near the Gulf Islands in May and June, then leave via the Strait of Juan de Fuca during late June and early July (Healey 1980).

Hartt and Dell (1986) reported mixed concentrations of juvenile pink, chum, coho, and sockeye salmon in the coastal waters of Southeast Alaska by late June. Landingham et al. (1987) found high concentrations of juvenile salmon of British Columbia origin along the outside waters of Southeast Alaska in July, while relatively large catches of juvenile Alaskan salmon were made in inside waters. In general, several studies have indicated that many juvenile salmon move north and then west along the Gulf of Alaska after leaving inside water and major concentrations occur within 20 miles of shore, except where the continental shelf is wider (Hartt and Dell 1986).

The distributions and migration routes for salmon from Southeast Alaska on the high seas have been coarsely inferred from results of tagging studies and generalized circulation patterns for the Gulf of Alaska. It is believed that some juvenile salmon from Southeast Alaska arrive in the vicinity of Kodiak Island around September and October, and that others disperse seaward earlier (Royce et al. 1968; Takagi et al. 1981). In general, immature salmon move away from northern continental shelf areas as sea temperatures fall in the Northeast Pacific (SST is lowest between February and April; see Section 3.6). Pink salmon bound for Southeast Alaska have been found (tagged) as far south as about 43°N during April and generally appear to reside east of about 155°W (Takagi et al. 1981; Royce et al. 1968).

Some coho salmon move offshore sooner than chum, sockeye, and pink salmon, while others never leave protected inside waters, and the position of others in the north-central Gulf during their first summer at sea suggests that some make a direct westward migration as juveniles (Godfrey et al. 1975; Hartt and Dell 1986). Coho salmon avoid cold seas, and their concentrations are the most southerly of the species (Manzer et al. 1965). High seas tagging results indicate that coho salmon bound for

Southeast Alaska between April and August are distributed mainly east of 150°W (Godfrey et al. 1975).

Tagging studies show that chum and sockeye salmon from Southeast Alaska are distributed east of 155°W between spring and fall, but it has been suggested that a more westerly winter distribution is possible than is evident from tagging (Neave et al. 1976; French et al. 1976). Both species migrate to avoid seasonally cold seas but are relatively tolerant and are generally found north of 46°N (Manzer et al. 1965; French et al. 1976; Neave et al. 1976). The high seas distributions of the salmonids originating from Southeast Alaska thus occurs within the Central Subarctic Domain, an area of fisheries production bounded by the Alaska Current, the Alaska Stream, and the Subarctic Current (Ware and McFarlane 1989).

Pink salmon are nearly all two years old at maturity, so that even-year and odd-year pink salmon catches can be considered to be from different populations. In contrast, most chum salmon in Southeast Alaska commercial harvests are probably 4 years old, although ages 5 and 3 are common (Buklis and Barton 1984; Clark et al. 1986). Five-year-old chum salmon are most common in catches in some areas of northern Southeast Alaska in some years (Clark et al. 1986).

Coho salmon 3, 4, and 5 years of age appear in Southeast Alaska commercial catches. Most coho salmon probably reach sexual maturity at 3 years in British Columbia and at 4 years in Southeast Alaska (Foerster and Ricker 1953; Crone and Bond 1976; Gray et al. 1981; Ricker 1981). Because some immature coho salmon remain near shore, they are taken in commercial fisheries before reaching maturity.

Sexual maturity in sockeye salmon commonly occurs at 4, 5 or 6 years and the principal age in the commercial catch may vary by fishery and by year (Foerster 1968). In 1985 most sockeye salmon in the catches and escapements of Southeast Alaska were 5 years old, and had spent one winter as juveniles in fresh water and 3 at sea (McPherson and McGregor 1986).

A summary of temporal relations between life history events and time in years before catch, as deduced from the preceding review, is shown in Table 2.2. This tabulation forms a basis for the interpretation of plausible relations between environmental and fisheries data presented in subsequent chapters.

Table 2.2. Average times of important life history events (in years before catch) for Southeast Alaska pink salmon that are 2, chum salmon that are 4, coho salmon that are 4, and sockeye salmon that are 5 years old at date of catch.

	Pink	Chum	Coho	Sockeye
Spawning				
Aug-Sep[a]	2	4		5
Oct-Nov			4	
Early marine				
May-Jun	1	3	1	3[c]
Coastal migration				
Jul-Oct	1	3	1[b]	3[c]
High seas residence				
Nov-Jun (8 mo)	0		0[b]	
Nov-Jun (8-32 mo)		2,1,0		2,1,0[c]

a In northern Southeast Alaska for pink, chum, and sockeye salmon; add one month for southern Southeast.
b Some coho salmon remain in coastal waters longer and do not make extensive migrations.
c Based on one winter rearing in fresh water.

CHAPTER 3
ENVIRONMENTAL INPUTS TO MODELS FOR SALMON FISHERIES IN SOUTHEAST ALASKA

Environmental variability undoubtedly contributes to the variation observed in salmon catch and abundance data. Early theorists reasoned that physical environmental factors tend to act independently of population density to eliminate a fraction of the population. These extrapensatory effects (Neave 1953) are generally believed to operate most during freshwater and early marine stages when natural mortality rates are highest (Parker 1962; Foerster 1968; Healey 1986).

Rationale is given in the following sections for considering air temperature, freshwater discharge, coastal upwelling, alongshore wind, and sea surface temperature (SST) in Southeast Alaska and the Northeast Pacific Ocean as extrapensatory effects. Times that salmon from Southeast Alaska are thought to reside in fresh water, interior marine, and Gulf of Alaska waters (Section 2.5) were then used to select temporal data which, I hypothesize, index the conditions experienced in each environmental domain.

Data from Sitka, Juneau, and Ketchikan, Alaska were obtained for some variables. Since salmon catches are compiled by area (northern, southern, and Southeast Alaska), I compiled similar summaries for the environmental data by averaging data for Sitka and Juneau to obtain a series for northern Southeast Alaska. Southern Southeast Alaska was represented by Ketchikan, and data for Ketchikan and northern Southeast Alaska were averaged to obtain a series for Southeast Alaska.

Seasonal mean values were computed from monthly data by weighting each monthly value by the number of days contributed to the season. Time series plots and seasonal cycles were also plotted.

3.1 Air Temperature

Anomalous temperatures in streams and redds may advance or delay spawning, egg development rates, and timing of juvenile emigrations (Sheridan 1962) or freeze eggs. Since long series of stream temperatures in Southeast Alaska were not available for an analysis, air temperature was used instead.

Mean December through February air temperature was adopted as an index to represent overall, temperature related, winter egg development and growth rate. Also, I used the annual minimum of the 7-day moving average of winter air temperature as an index which might relate to egg mortality caused by extreme, short-term temperatures.

Daily (TD-3200 Summary of the Day) air temperature data from the National Oceanic and Atmospheric Administration, National Climatic Data Center (NCDC) in Asheville, North Carolina were obtained through U S WEST Optical Publishing Co. in Denver, Colorado. All daily minimum and maximum records for Ketchikan, Annette, Juneau, and Sitka available in electronic form were obtained for the analysis. The electronic database generally begins in September 1949, except that data for the Sitka Magnetic Observatory begin in April 1899. The NCDC electronic records are 95% or more complete (see below) except for downtown Juneau (86%) and Ketchikan (88%). All data not found in the NCDC electronic files were checked against hard copy U.S. Weather Bureau climatological records for accuracy. In many cases, absence from the electronic files signified only that data (typically for a month) had not been keypunched.

Daily temperature observations missing from the NCDC electronic files (due to incomplete data entry) and all monthly mean temperatures predating the first machine readable record for each station were obtained from annual U.S. Department of Agriculture Reports (USDA 1912) or U.S. Weather Bureau climatological summaries for Alaska (USWB 1915; USWB 1940). Monthly mean temperatures were calculated as the mean of temperatures for each day during the whole month. The temperature used for each day was an average of the day's low and high temperatures.

Temperatures never recorded (due to construction, instrument failure, sickness, etc.) were estimated by linear interpolation if the missing values were isolated daily observations. Otherwise, observations from a nearby station were substituted after seasonal corrections for differences in location were determined. Construction of the time series is detailed in Appendix B.

Mean annual air temperatures (Figure 3.1) show a series of peaks and troughs as described by Hamilton (1965) and Juday (1984). Five-year moving averages suggest temperature trends in Ketchikan notably different from those in Sitka and Juneau, especially before 1940. Mean annual temperatures in Juneau and Sitka (Figure 3.1) appear to oscillate with periods of about 15 to 22 years.

The annual cycle of monthly air temperatures in Juneau peaks before Ketchikan or Sitka (Figure 3.2), illustrating a difference in climate. Mean winter (December

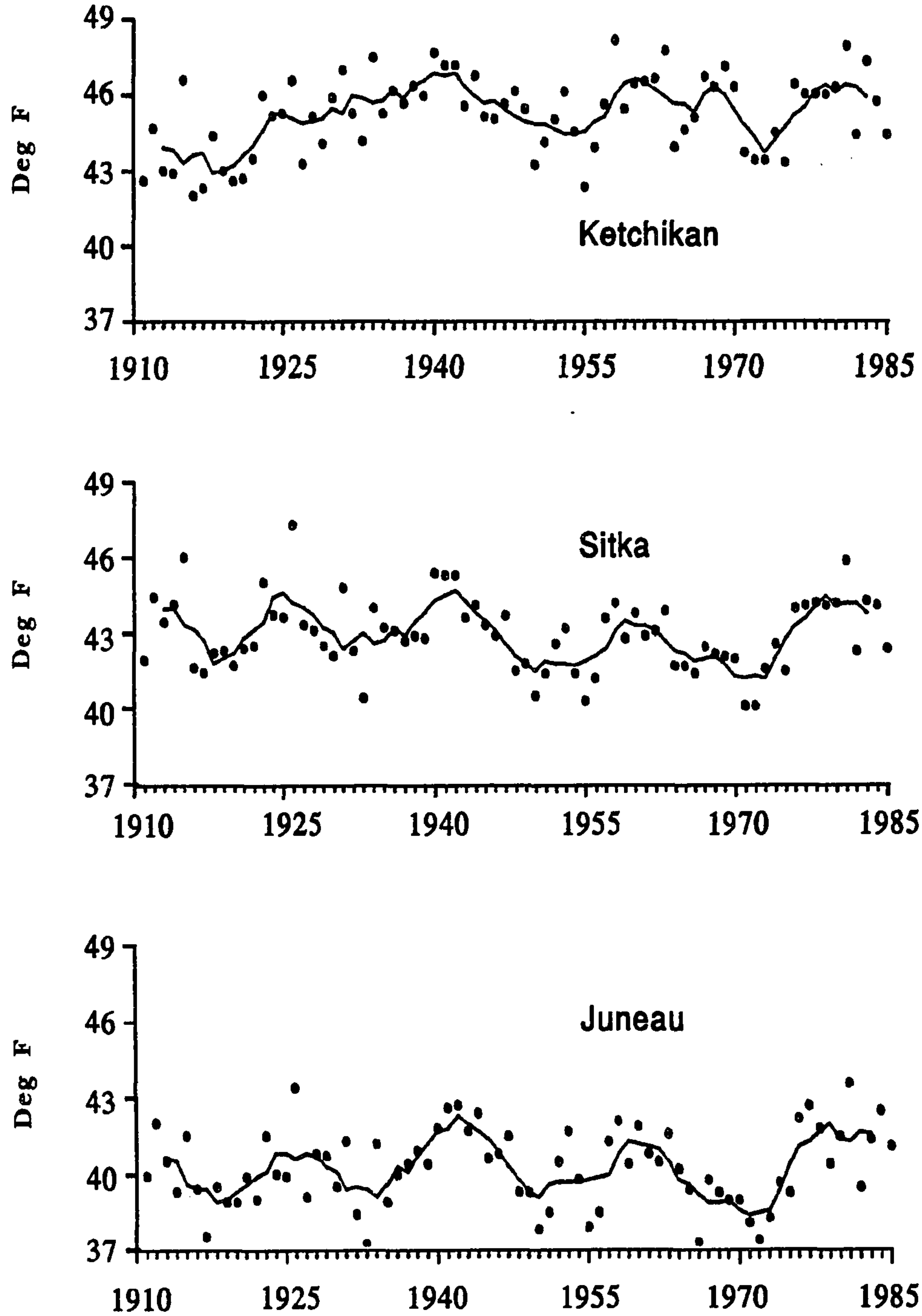


Figure 3.1. Mean annual air temperature (dots) and 5-year moving average of mean annual temperature (line) in Ketchikan, Sitka, and Juneau, Alaska.

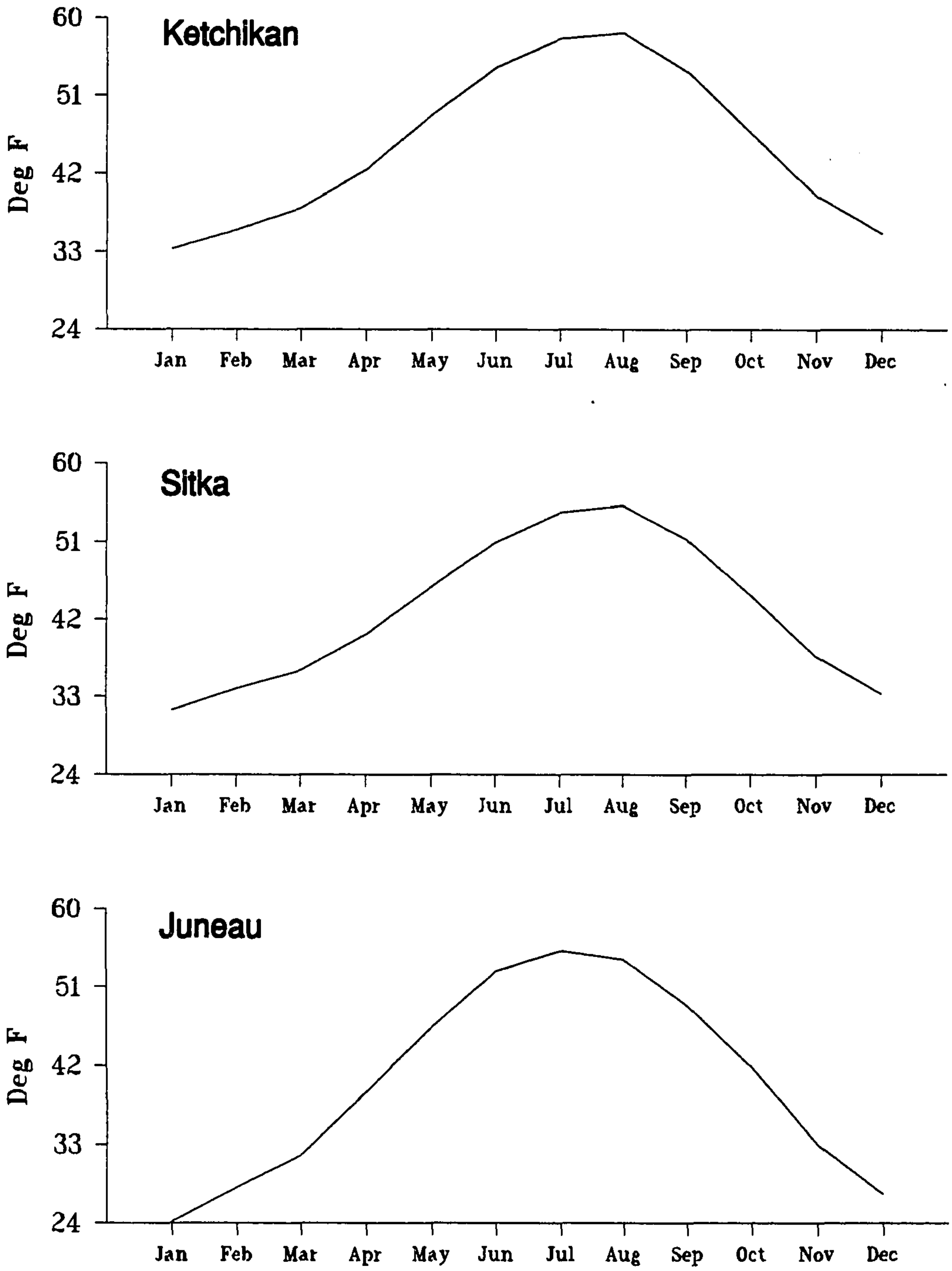


Figure 3.2. Seasonal cycles of mean monthly air temperatures in Ketchikan, Sitka, and Juneau, Alaska.

through February) air temperatures (Figure 3.3) illustrate similarities in the climates at each location, as do low winter temperatures (Figure 3.4). Time series of winter temperatures for northern Southeast Alaska (mean of Sitka and Juneau) and Southeast Alaska (mean of southern and northern Southeast) are shown in Figure 3.5.

3.2 Freshwater Discharge

Wickett (1958) describes losses in salmon production related to anomalous stream flows, a) during the spawning season, b) during October or November, and c) during high flows which scour eggs from redds. Agents for loss in a) and c) are low water levels which impede successful spawning and high flow rates which move spawning gravel, respectively. The agent of loss in b) was thought to be delivery of oxygen to developing eggs. In Hooknose Creek, however, Hunter (1959) found no significant correlation between the egg-to-fry survival of pink and chum salmon, and September and October discharges between 1947 and 1957. Similarly, Merrell (1962) reported no consistent relationships between runoff and the survival of pink salmon in Sashin Creek.

Low stream flows during the first summer of life were consistently correlated with abundance of coho salmon runs in Puget Sound (Mathews and Olson 1980), apparently because of a relationship between flows and survival of stream resident juveniles. However, similar relations were poorly defined in coastal Oregon streams (Nickelson and Lichatowich 1984). Because pink and chum salmon migrate to salt water quickly after emergence, and sockeye salmon fry typically rear in lakes, anomalous summer discharges are probably not as critical for these species as for coho salmon.

Average stream flows during spawning (Table 2.2) were adopted for an index which might relate to spawning success, although stream discharges and stream levels may not be linearly related. An index for destruction of salmon redds by flood events was not constructed because long time series of daily stream flows for Southeast Alaska were not found. However, an index which might relate to in-stream survival of coho salmon fry was constructed from the two-lowest consecutive monthly summer (June-September) discharges, after Mathews and Olson (1980), who used 60 consecutive days of low flows as an index.

Long series of stream discharges for Southeast Alaska were not found, except as noted below. Thus, monthly mean discharges of fresh water (1931-1985) modeled from U.S. Weather Service precipitation and air temperature data between about 130°W and 140°W (Royer 1982) were obtained as an index for Southeast Alaska. Temperature

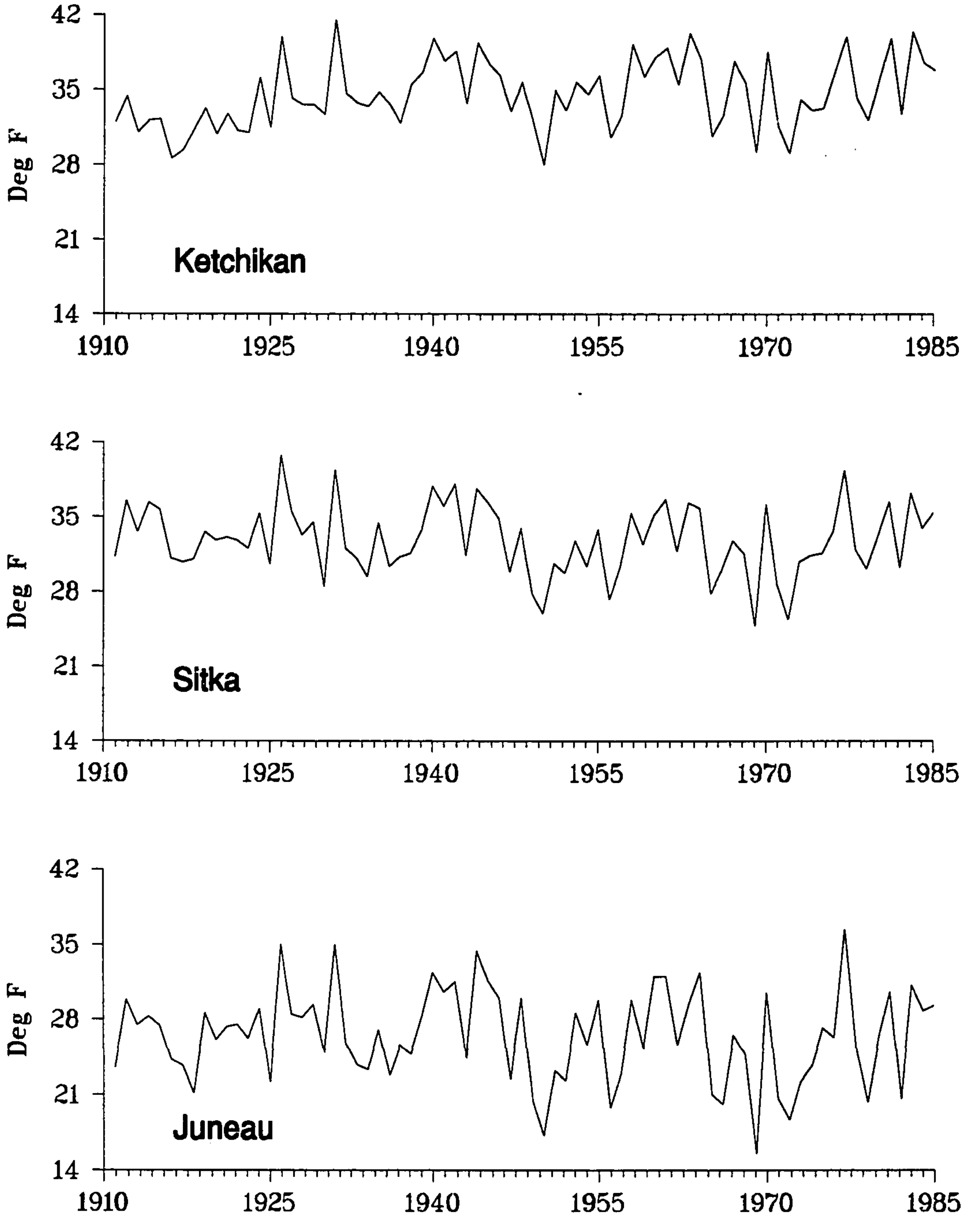


Figure 3.3. Mean winter (December through February) air temperatures in Ketchikan, Sitka, and Juneau, Alaska.

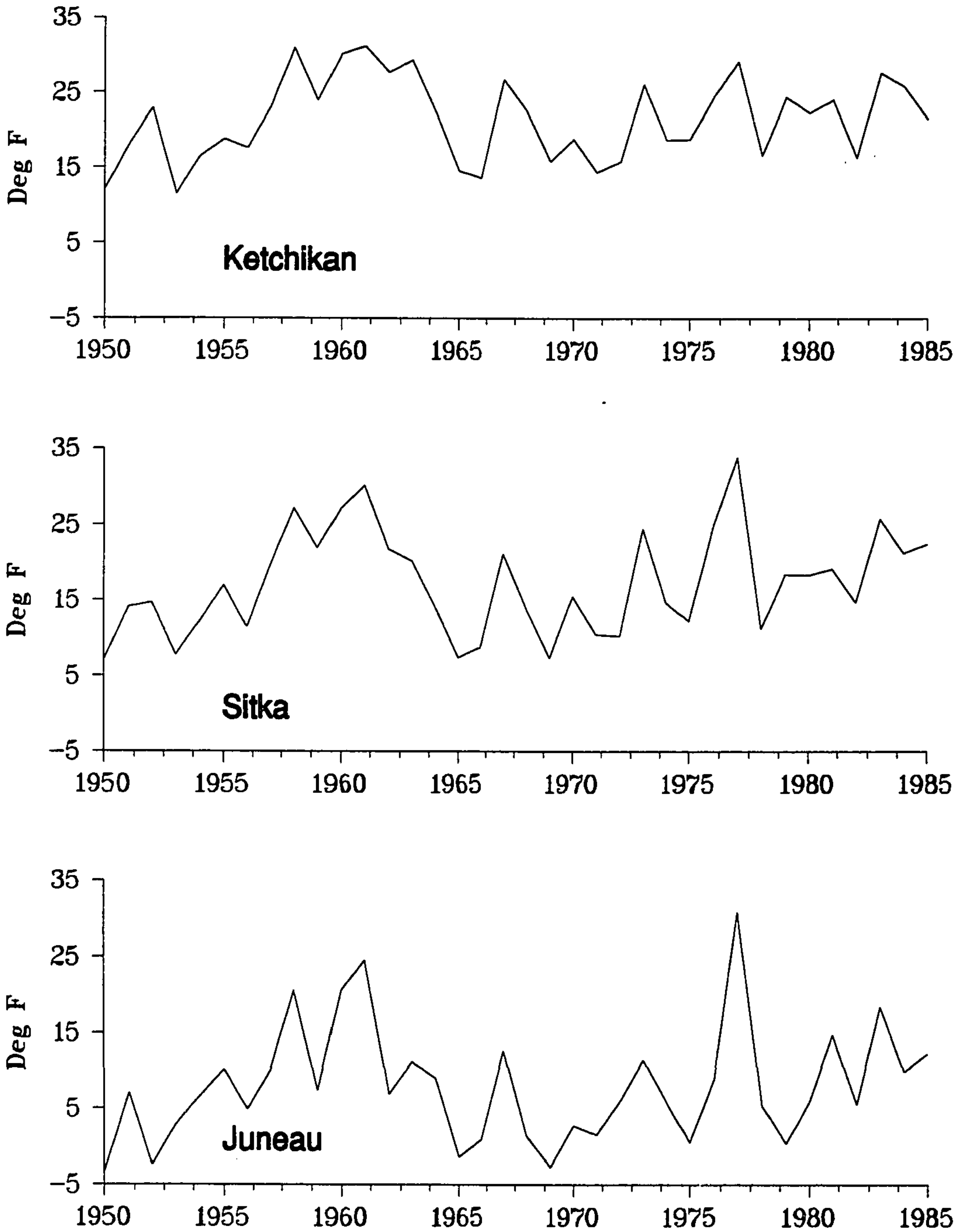


Figure 3.4. Low (7-day minimum) winter air temperatures in Ketchikan, Sitka, and Juneau, Alaska.

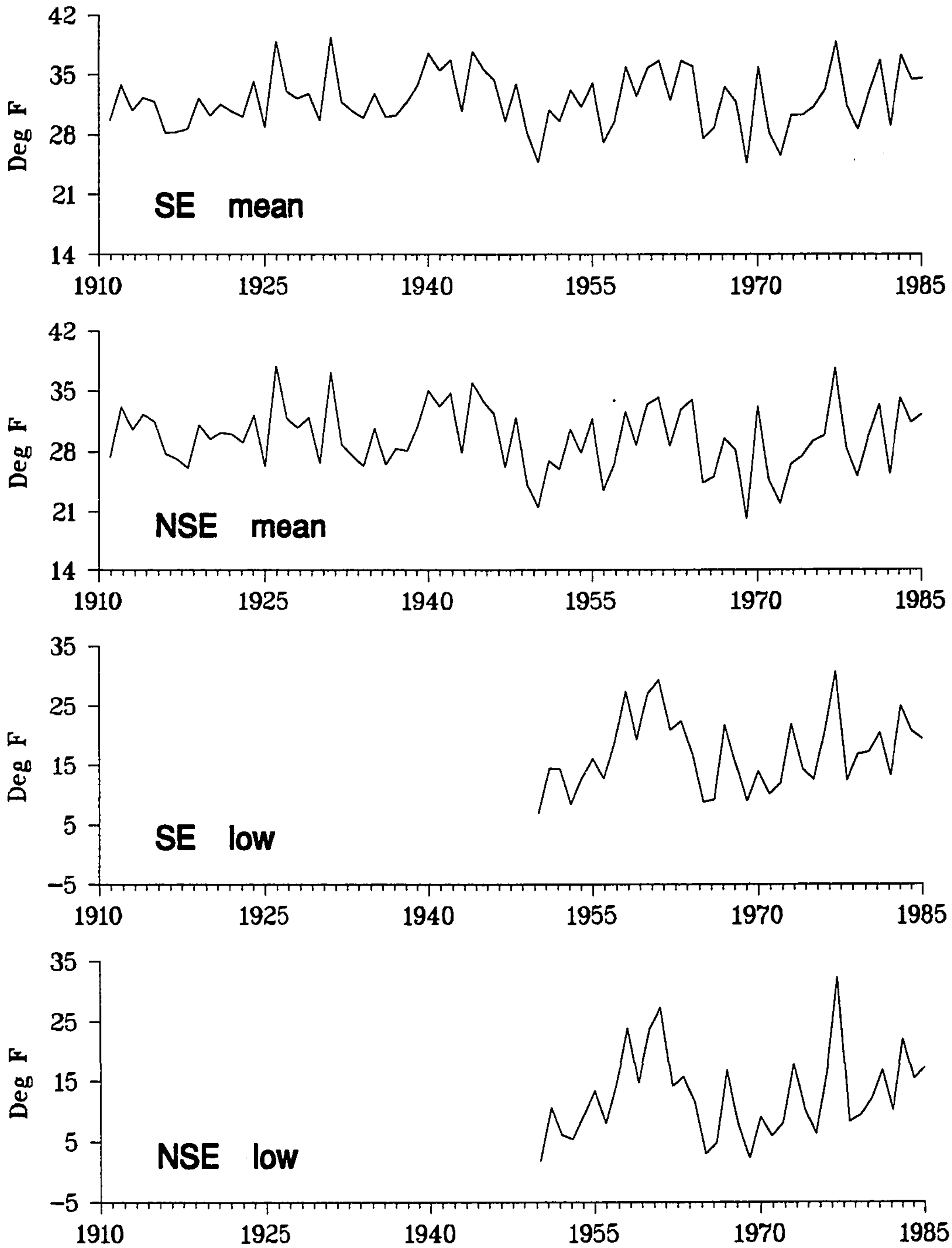


Figure 3.5. Mean winter (December through February) and low (7-day minimum) winter air temperatures in Southeast (SE) and northern Southeast (NSE) Alaska.

controls growth and ablation of snow fields and glaciers in the model. Freshwater discharges obtained from the model correlate well with estimates of alongshore baroclinic transport near Seward (r=0.763 for 1974-1980, Royer 1982).

Modeled freshwater discharges for Southeast Alaska (Dr. T.C. Royer, University of Alaska, Fairbanks, personal communication) were compared to monthly mean runoff data for Fish Creek drainage on Revillagigedo Island, near Ketchikan (Dr. W.A. Smoker, National Marine Fishery Service (NMFS), Auke Bay, Alaska, personal communication). Correlation between Fish Creek and Southeast Alaska monthly discharges (Figure 3.6) is 0.67. Time series of seasonal discharges coincident with salmon spawning across Southeast Alaska were thus obtained from both data sets as the mean of monthly mean discharges during months of spawning (Table 2.2) for each species. Correlations between the seasonal discharges from the modeled (Royer 1982) and Fish Creek data range from r=0.69 to r=0.76. Since seasonal (fall) discharge cycles for the two data sets are similar (Figure 3.7), modeled data for Southeast Alaska were adopted for further use.

Plots of mean seasonal freshwater discharges during pink, chum, and sockeye salmon spawning are shown in Figure 3.8. Time series of low summer and spawning discharges for coho salmon are shown in Figure 3.9.

3.3 Inland Marine SST

Natural mortality rates for salmon in the ocean are generally thought to be greatest during the first year at sea. Sea surface temperature during a salmon's early marine residence may thus be a good indicator of environmental conditions during this period. Donnelly (1983), for example, found high correlations (r=0.73 to r=0.85) between fry to adult survival of pink salmon in the Kodiak Archipelago and spring and summer temperatures in Kodiak Bay. I adopted an average of May and June SST as an index of temperature conditions occurring when juvenile salmon first reside in inland marine waters in Southeast Alaska (Table 2.2).

Monthly mean surface water temperatures measured at tide gauges in Ketchikan, Sitka, and Juneau, Alaska, were obtained from the National Oceanic and Atmospheric Administration, National Ocean Services Sea and Lake Levels Branch, in Rockville, Maryland. The same data, through 1955, are also found in USCGS (1956). According to USCGS (1956), the measurements are thermometer readings from water drawn by bucket from a foot or two below the surface. Monthly mean temperatures at Ketchikan from 1922, and in Sitka Harbor and at Juneau from 1944 were entered for analyses

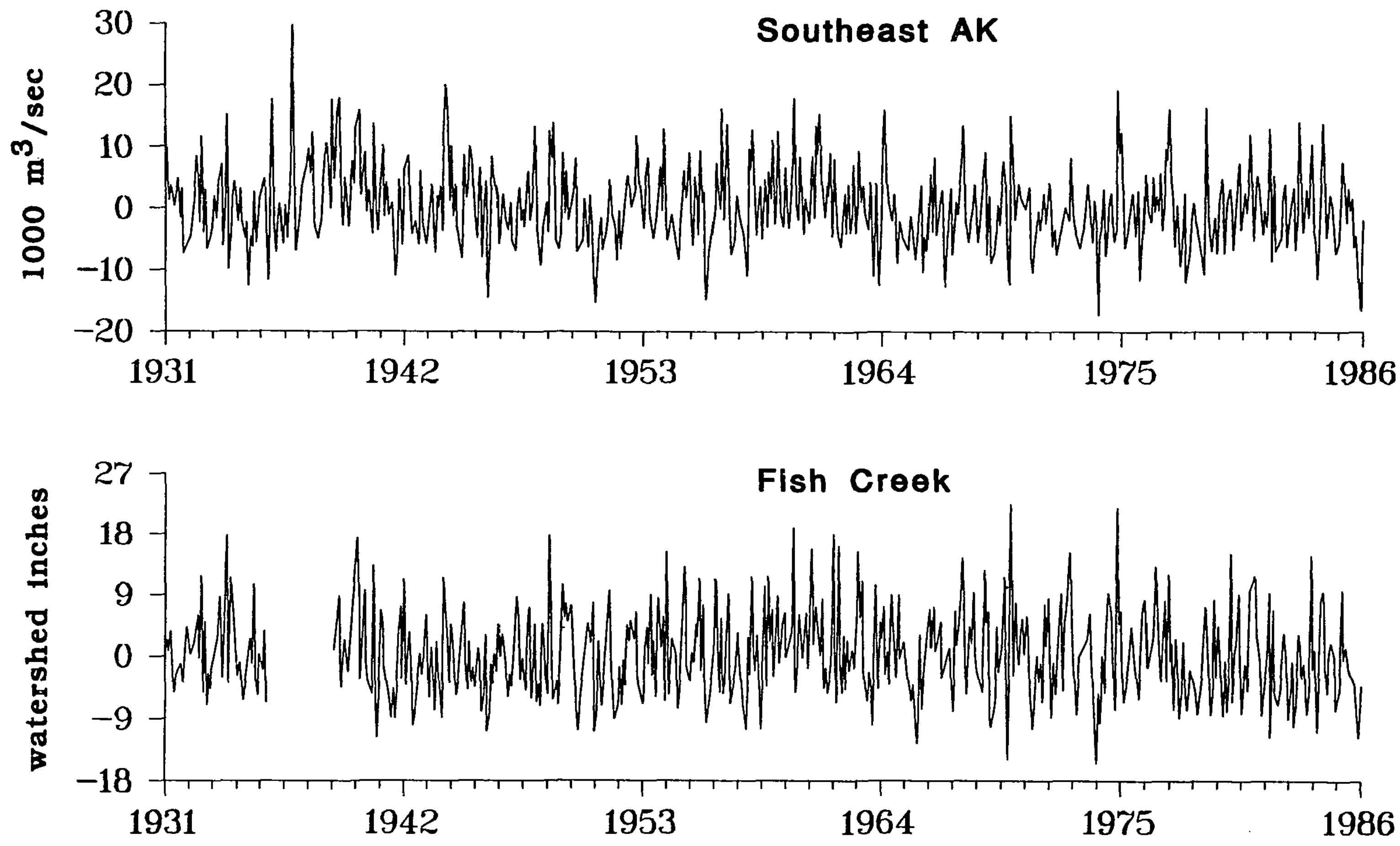


Figure 3.6. Anomalous mean monthly freshwater discharges from Southeast Alaska (Royer 1982) and Fish Creek, Alaska.

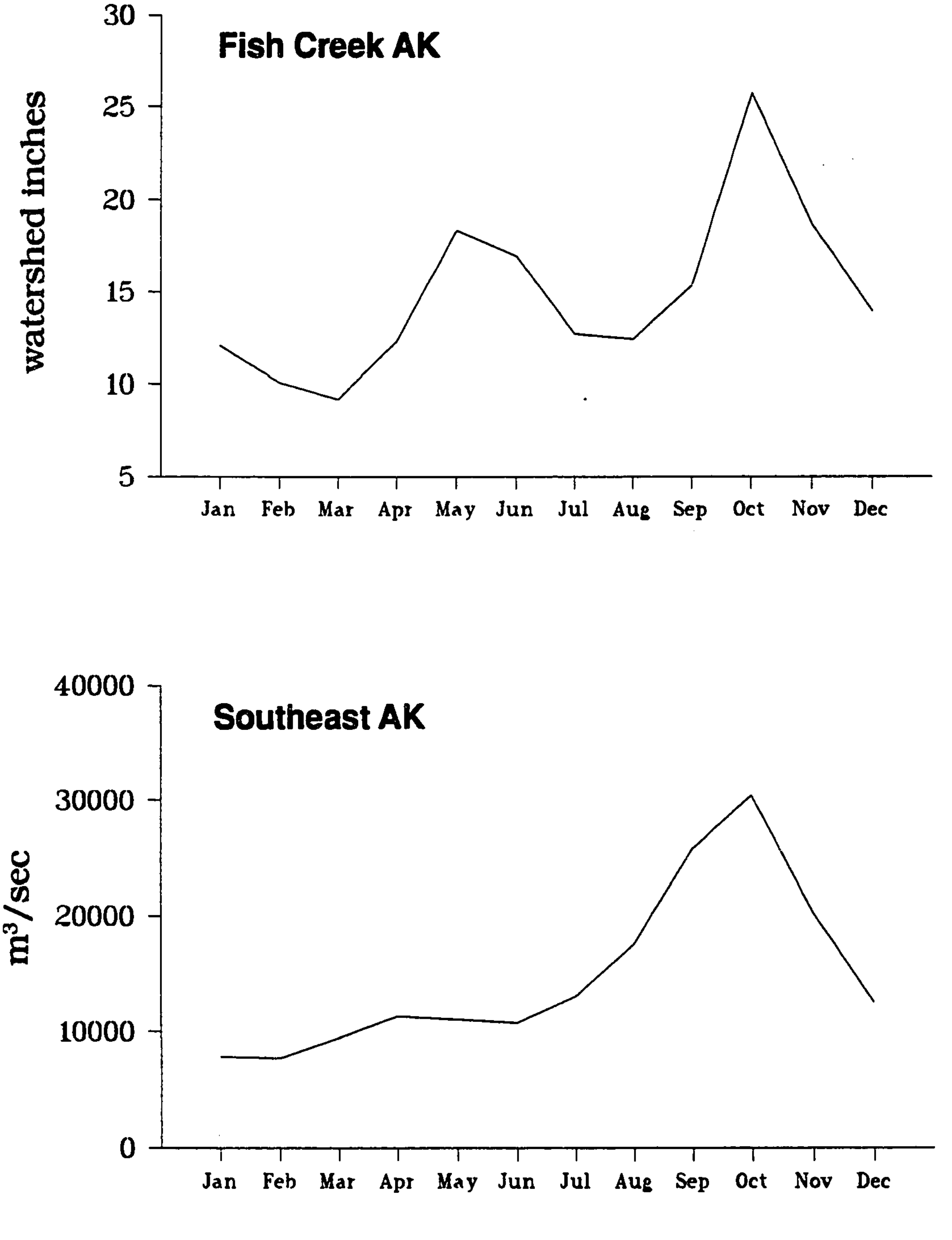


Figure 3.7. Seasonal cycles of mean monthly freshwater discharge for Fish Creek and for Southeast Alaska.

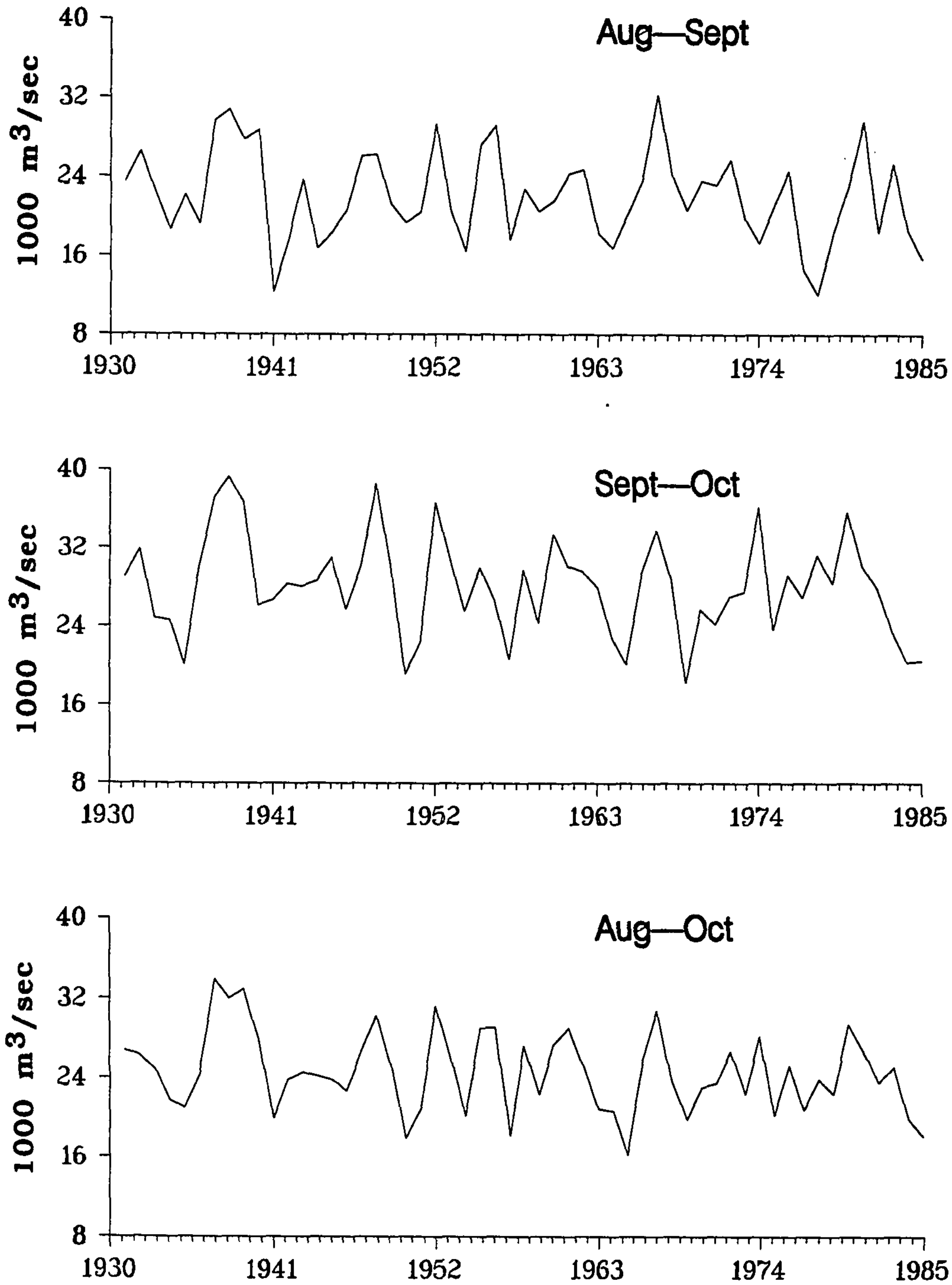


Figure 3.8. Mean seasonal freshwater discharges from Southeast Alaska during periods of pink, chum, and sockeye salmon spawning in northern (Aug-Sept), southern (Sept-Oct), and Southeast (Aug-Oct) Alaska.

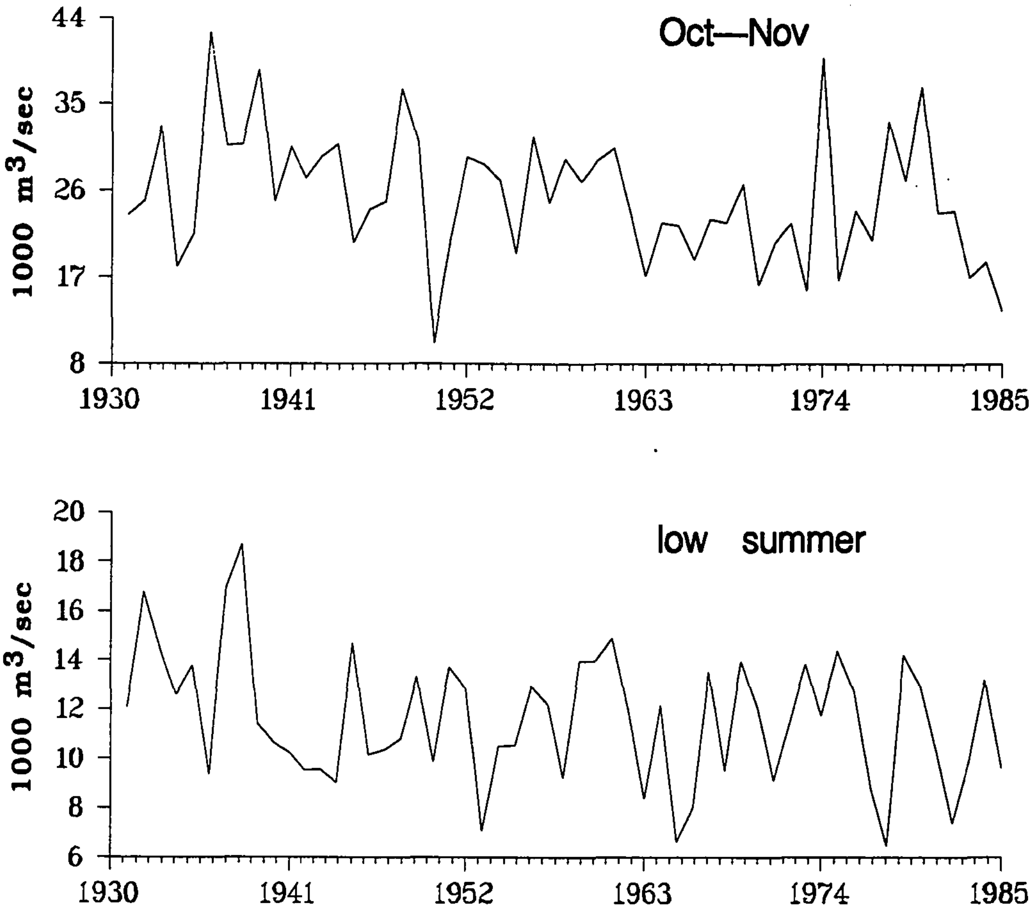


Figure 3.9. Mean seasonal freshwater discharges from Southeast Alaska during the period of coho salmon spawning (Oct-Nov), and during low summer (2-month minimum) flows.

(Figure 3.10). The seasonal cycle of monthly mean temperatures at Sitka and Ketchikan are very similar, while seasonal temperatures in Juneau are more variable and peak earlier in July (Figure 3.11).

Missing monthly mean temperatures for Ketchikan in May 1981 and June 1968, 1978, 1981, and 1982 were predicted in a multiple regression, so that a complete time series of May and June temperatures could be formed. Predictor variables were selected from among April, May, June, and July surface water temperatures at Sitka, and from May and June air temperatures in Ketchikan. Regressions with parameter estimates not significant at two standard errors were discarded. The regression with the highest value of r^2 was then used to predict temperature anomalies for the 5 missing data. Series of average May plus June water temperatures in Ketchikan, northern Southeast Alaska (mean of Sitka plus Juneau), and Southeast Alaska (mean of northern Southeast and Ketchikan) were summarized for analyses (Figure 3.12).

Other SST data for Southeast Alaska has been collected at U.S. Coast Guard lighthouses. However, these data collections are relatively short; data was located for 1959 to 1974 only (Williamson 1965; Jones 1978).

3.4 Coastal Upwelling

Coastal upwelling has received considerable attention in discussions of pelagic and coho salmon fisheries along the coast of North America (Bakun and Parrish 1980; Pearcy 1984) since upwelling tends to increase regional food production. Although surface winds along Alaska's coast do not favor strong upwelling (Bakun 1973) other relationships between juvenile salmon and wind stress are possible. For example, winds generating strong onshore Ekman flows might transport oceanic surface water and biota to the continental shelf, changing the types of food available to migrating juveniles (Cooney 1984, 1987). Also, alongshore winds near Seward, Alaska can be related to alongshore current speeds (Section 3.5).

An index which might be related to the growth and survival of juveniles feeding along the coast of Southeast Alaska is the mean of coastal upwelling indices (UWI) in June and July. Although July is hypothesized to be the time juvenile fish enter outside waters (Table 2.2), a one-month lag was introduced to represent the set-up time for production of food items usable at higher trophic levels (Bakun and Parrish 1980). In addition, June and July are months of peak upwelling in Southeast Alaska (Bakun 1973).

Monthly upwelling indices at four locations near the coast of Alaska from January

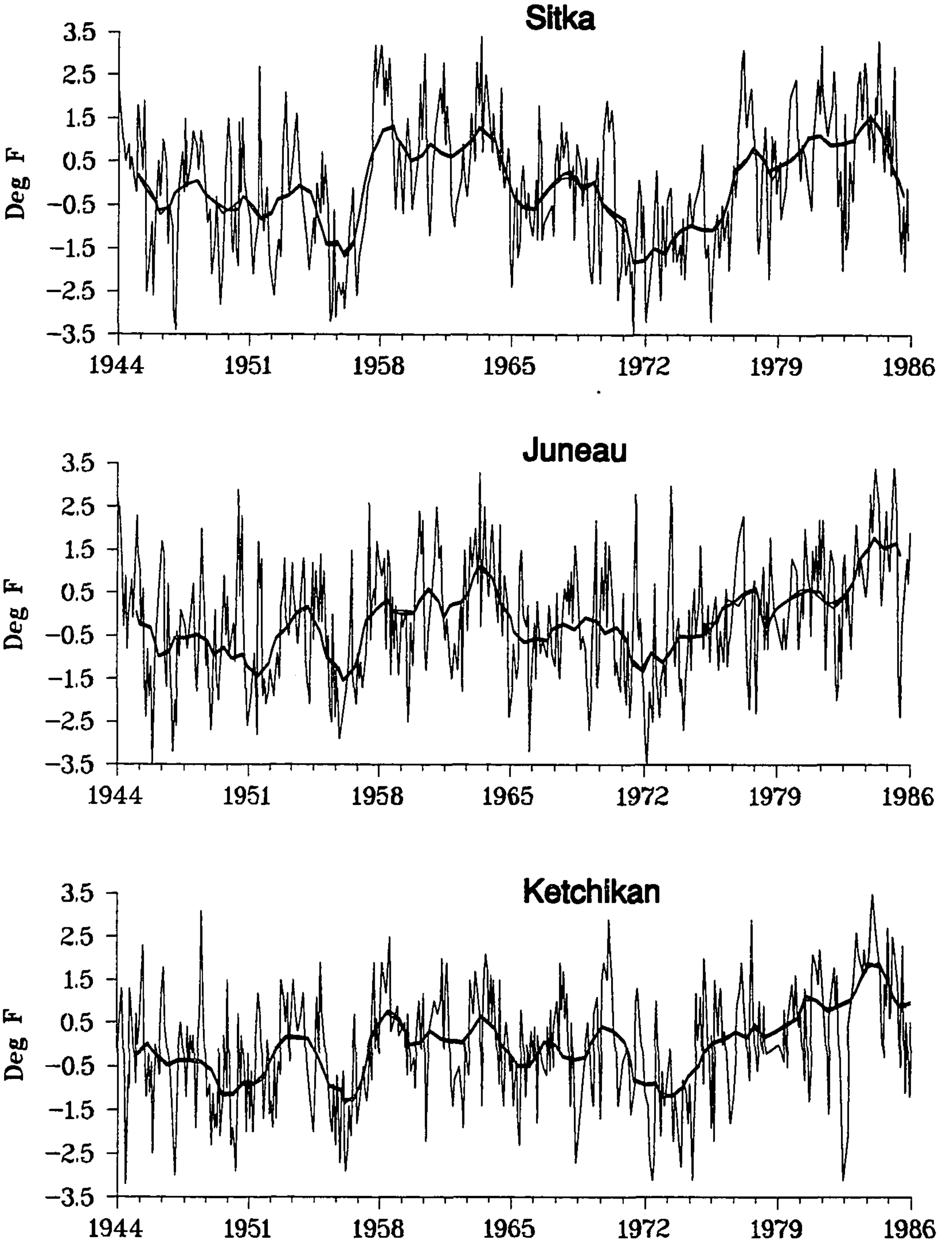


Figure 3.10. Anomalous mean monthly sea surface temperatures (SST) in Sitka, Juneau, and Ketchikan, Alaska. A 5-year moving average of mean annual SST is superimposed on the monthly data.

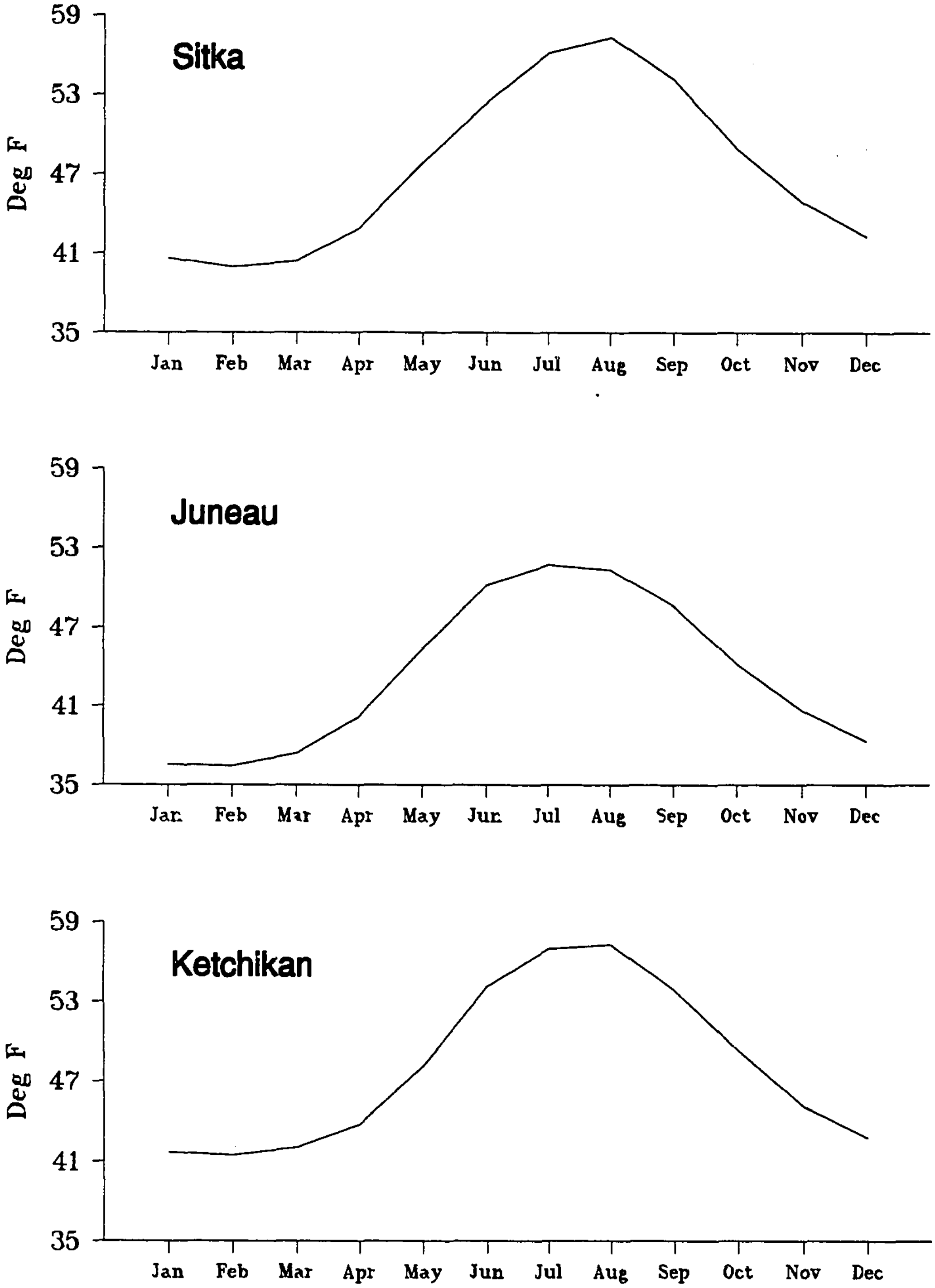


Figure 3.11. Seasonal cycles of mean monthly sea surface temperatures in Sitka, Juneau, and Ketchikan, Alaska.

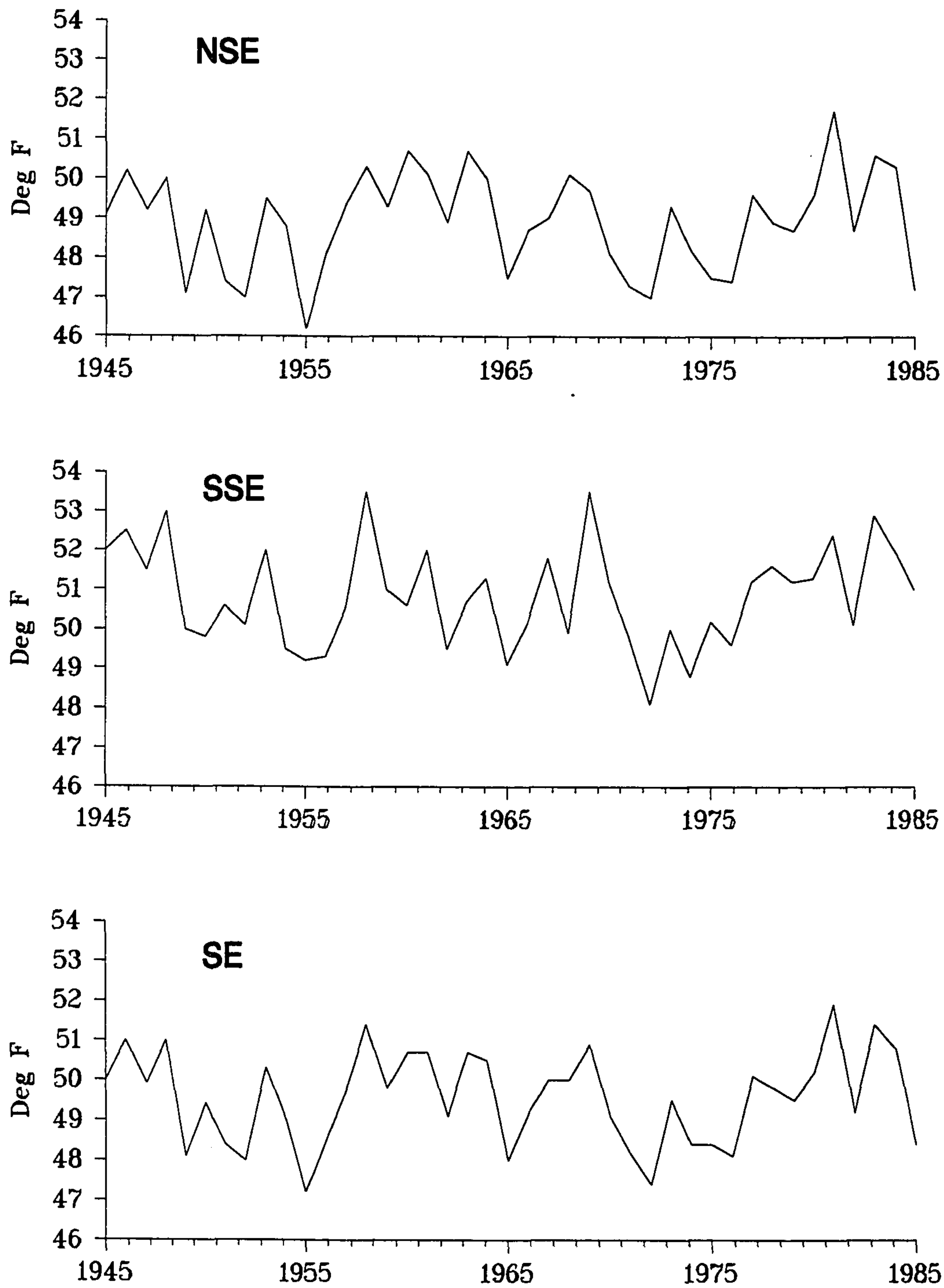


Figure 3.12. Mean of May and June sea surface temperatures in northern Southeast (NSE), southern Southeast (SSE) and Southeast (SE) Alaska.

1946 onward are described by Bakun (1973) and Mason and Bakun (1986). Electronic copies of these data were obtained from Andrew Bakun (Pacific Environmental Group, NMFS, Monterey, California, personal communication). The locations are at 54°N 134°W (about 40 miles west of the northern tip of Graham Island), at 57°N 137°W (about 40 miles west of Sitka), at 60°N 146°W (about 40 miles south of Cordova), and at 60°N 149°W (near Seward).

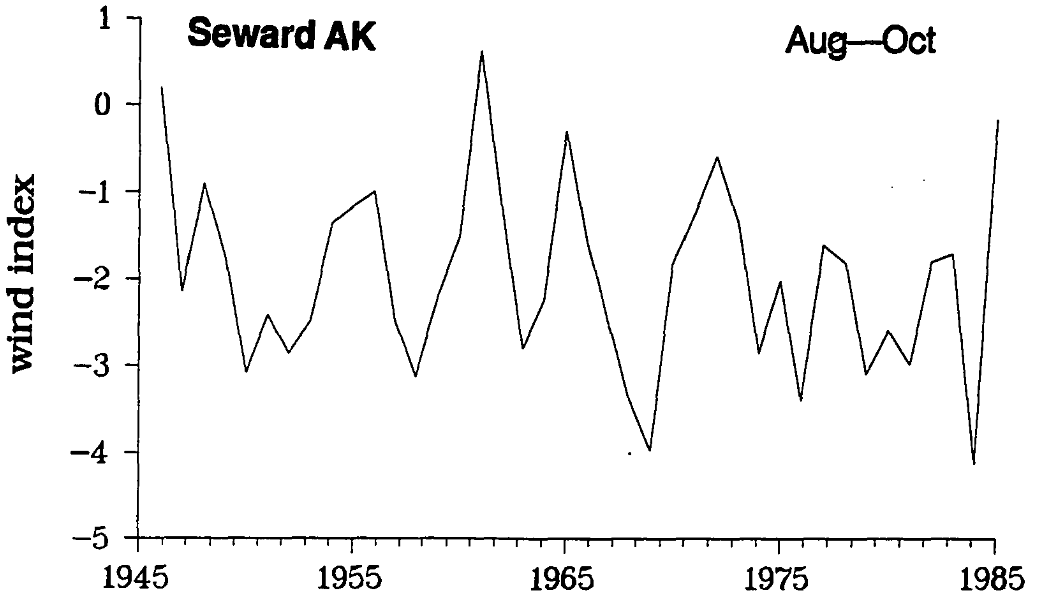
Upwelling indices in June and July at 54°N 134°W and 57°N 137°W were averaged for the analyses (Figure 3.13).

3.5 Alongshore Winds

The Alaska Coastal Current, which is driven by downwelling favorable winds and freshwater discharge, has been described in a series of investigations (Royer 1975, 1981, 1982; Luick et al. 1987; Johnson et al. 1988). The spatial domain of this flow matches the domain for offshore migrations of juvenile salmon traversing the coast of Alaska. Thus, it is reasonable to hypothesize that anomalous flows in the coastal current are related to growth and/or mortality of salmon during a coastal migration.

Luick et al. (1987) and Johnson et al. (1988) used empirical orthogonal functions to show that near Seward, Alaska, the first mode (explaining 68% of variance in alongshore current velocity) was barotropic and was strongly related (r^2=0.71) to alongshore wind. The second mode (explaining 17% of variance in alongshore current velocity) was related (r^2=0.46) to freshwater discharge. Thus, the seasonal variability in current speed was related to changes in alongshore winds near Seward. Since the measured currents were largely barotropic, the winds probably reflected (the statistical) changes in the location of the North Pacific High and Aleutian Low pressure systems.

Upwelling indices contain information about alongshore wind speed. An index which might relate to effects experienced by salmon traversing the Alaska Coastal Current was thus constructed from upwelling indices (Section 3.4) at stations where flows of the current during a migration could be related to alongshore wind speed. Monthly upwelling indices at 60°N, 146°W and at 60°N, 149°W (Bakun 1973; Mason and Bakun 1986) were thus converted to an index of alongshore wind speed. Following Bakun's (1973) notation, wind vector $\underline{v}$ having magnitude $|\underline{v}|$ is related to mass transport M (the upwelling index) by:



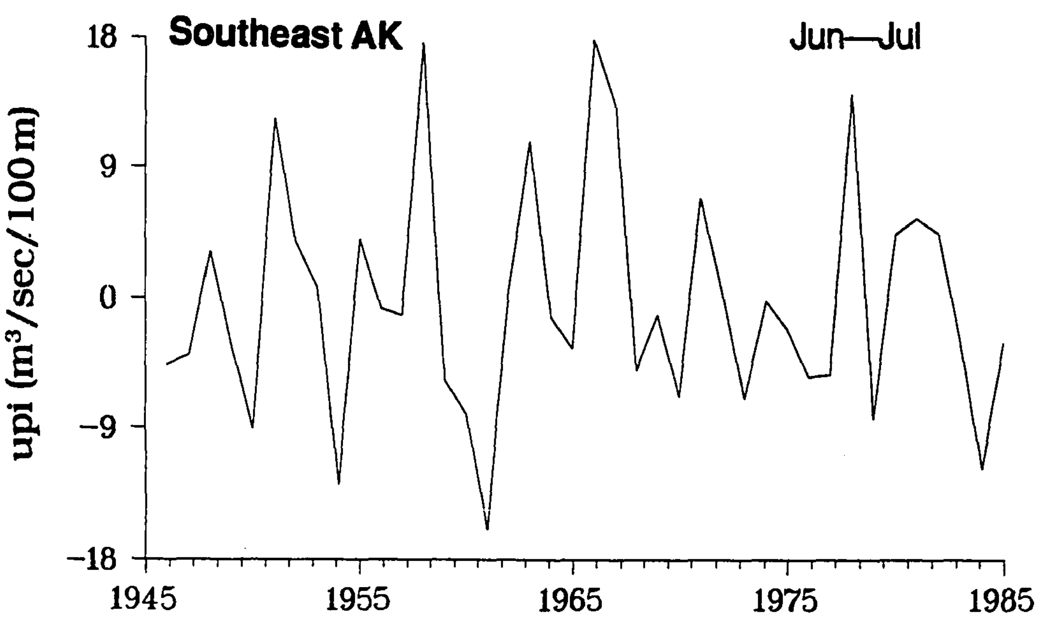


Figure 3.13. Mean of June and July upwelling indices for Southeast Alaska (upi), and August-October alongshore wind speed indices near Seward, Alaska.

$$M = \frac{\rho_\alpha C_\phi |\underline{v}| \underline{v}}{\mathscr{F}}$$

where ρ_α (density of air), C_ϕ (drag coefficient), $\mathscr{F}$(Coriolis parameter) are constants (at 60°N). A wind speed index was thus obtained as $\sqrt{M}$ if M>0 or as $-\sqrt{|M|}$ if M<0. The derived indices at the two stations are highly correlated in August (r^2=0.92), September (r^2=0.94), and October (r^2=0.92), when juvenile migrations traverse the coast of Alaska. The monthly indices are uncorrelated across months (r<0.25). An overall index for coastal migrations was formed by averaging the indices across months (August-October) and the two stations (Figure 3.13).

3.6 Northeast Pacific Sea Surface Temperature

Variations in sea temperatures, or covariates thereof, may affect the growth or survival of salmon because they are poikilotherms or because of broader ecological interactions (Killick and Clemens 1963; Helle 1979; Barber and Walker 1980; Ricker 1981; Skud 1982; Donnelly 1983; Willette 1985; Healey 1986; Blackbourn 1987). The principal problem in summarizing SST for comparison to salmon data lies in choosing coincident spatial and temporal domains. On the basis of information contained in maps of high seas salmon distributions (see Section 2.4), SST east of 160°W and north of 40°N covers the major distributions of salmon from Southeast Alaska. SST's at 3 latitudes (55°N, 50°N, 45°N) are thus available for indices, as discussed below. After pink salmon leave the continental shelf they may move south of 45°N, then back (to 55°N) between November and July (Royce et al. 1968), and coho salmon may behave similarly, since they prefer warm seas (Manzer et al. 1965). An index which averages latitudinal temperature variations over this period would provide a reasonable index for these species. For maturing chum and sockeye salmon, averaging SST at 50°N in winter (January through April) and averaging SST at 55°N in summer (July through October) provides two seasonal indices for these species. The index for summer SST at 55°N may also indicate temperature conditions experienced by juvenile salmon traversing the northern Gulf of Alaska between July through October in their first summer at sea.

Monthly means of SST compiled from ships of opportunity on a 5° latitude by 5° longitude grid of the North Pacific Ocean from 1947 were obtained from Dr. T.C. Royer (University of Alaska, Fairbanks, personal communication). No observations are recorded at 60°N, 145°W until 1965, and 20 months of data at 55°N, 135°W are missing between December 1950 and 1960, so data at these stations are not usable for this analysis. Averaging SST across remaining stations is complicated by sparse sampling at some stations before 1954. A data set was thus constructed using data from stations at 155°W, 150°W, 145°W, and 140°W at each latitude (55°N, 50°N, and 45°N) starting with November 1950. Sixteen missing observations were estimated in order to minimize biasing averages across stations; since monthly SST anomalies at each station are highly autocorrelated, missing values were obtained by interpolating from the series of anomalies.

The distribution of SST changes dramatically as one moves from 55° southward to the latitude of the West Wind Drift (Figure 3.14). Seasonal amplitudes of the temperature cycle increases between 55°N and 45°N, but otherwise appears quite similar (Figure 3.15).

SST from November through June at all stations, from January through April at 50°N, and from July through October at 55°N, were averaged for analyses (Figure 3.16).

3.7 Summary

Time series of environmental data extending from 1911 were collected and analyzed. Most of the data were obtained as monthly mean values, except that daily air temperatures at some stations are available. Linear interpolations, correlations, and regressions were employed to estimate a small number of missing data values, so that long time series could be formed and aggregations of data would be minimally biased. Electronic files and other data for air and inland sea surface temperature appear to require extensive processing to obtain reliable data on climate changes.

Salmon life history information (Chapter 2) was used to determine the temporal and spatial scales for aggregating environmental data. The resulting time series (Table 3.1) reflect local, regional, and very large scale fluctuations in environmental conditions which affect salmon populations of Southeast Alaska. When single age classes of each species dominate in the catches each year, a restricted set of lag-relations between the environmental and fisheries time series are expected to be important (Table 3.2). These relations, which are derived from the information in Table 2.2, can be used to judge whether statistical associations between fisheries and the environmental time series have potentially understandable causal relations.

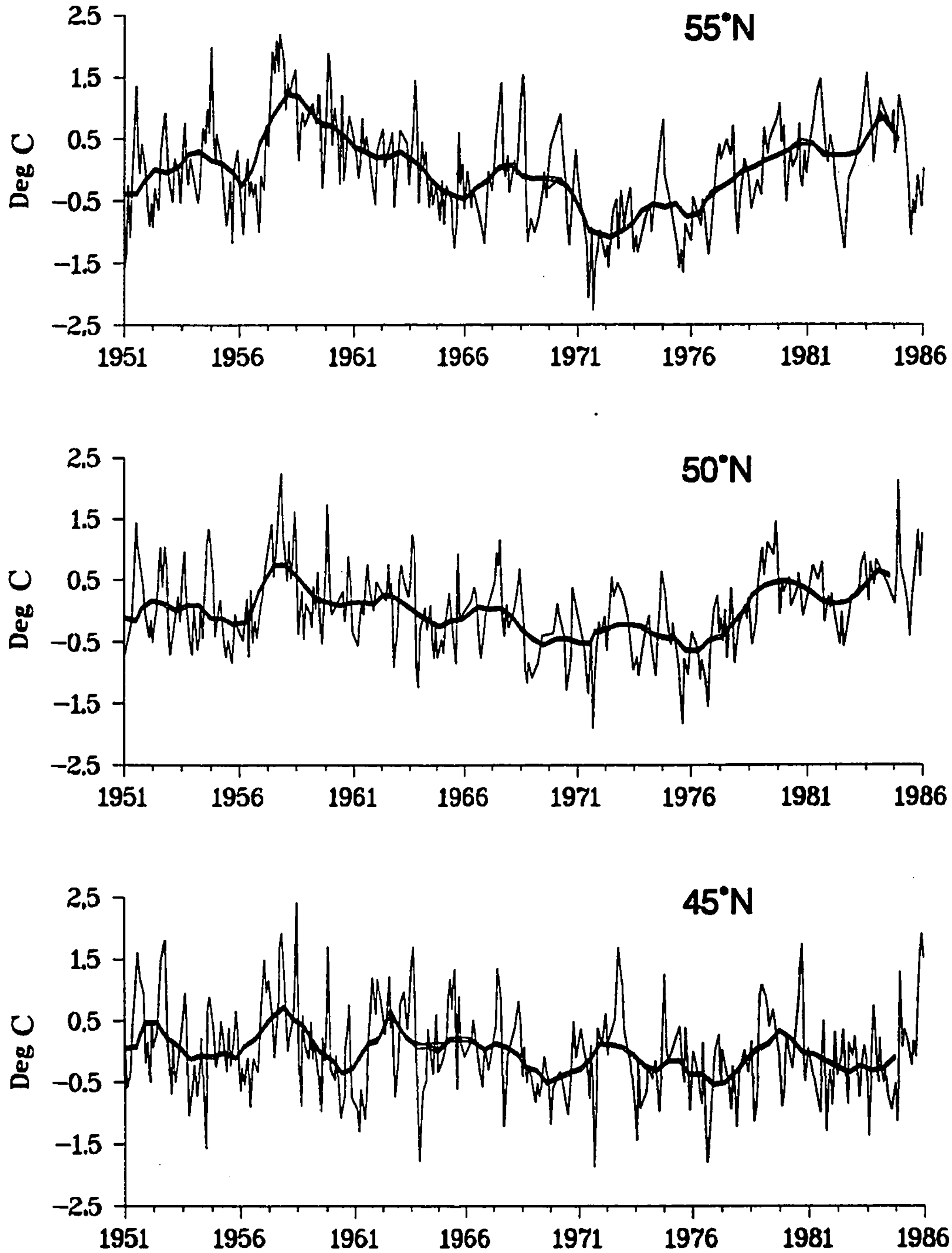


Figure 3.14. Anomalous mean monthly NE Pacific Ocean sea surface temperatures (SST) at 55°N, 50°N, and 45°N. A 5-year moving average of mean annual SST is superimposed on the monthly data.

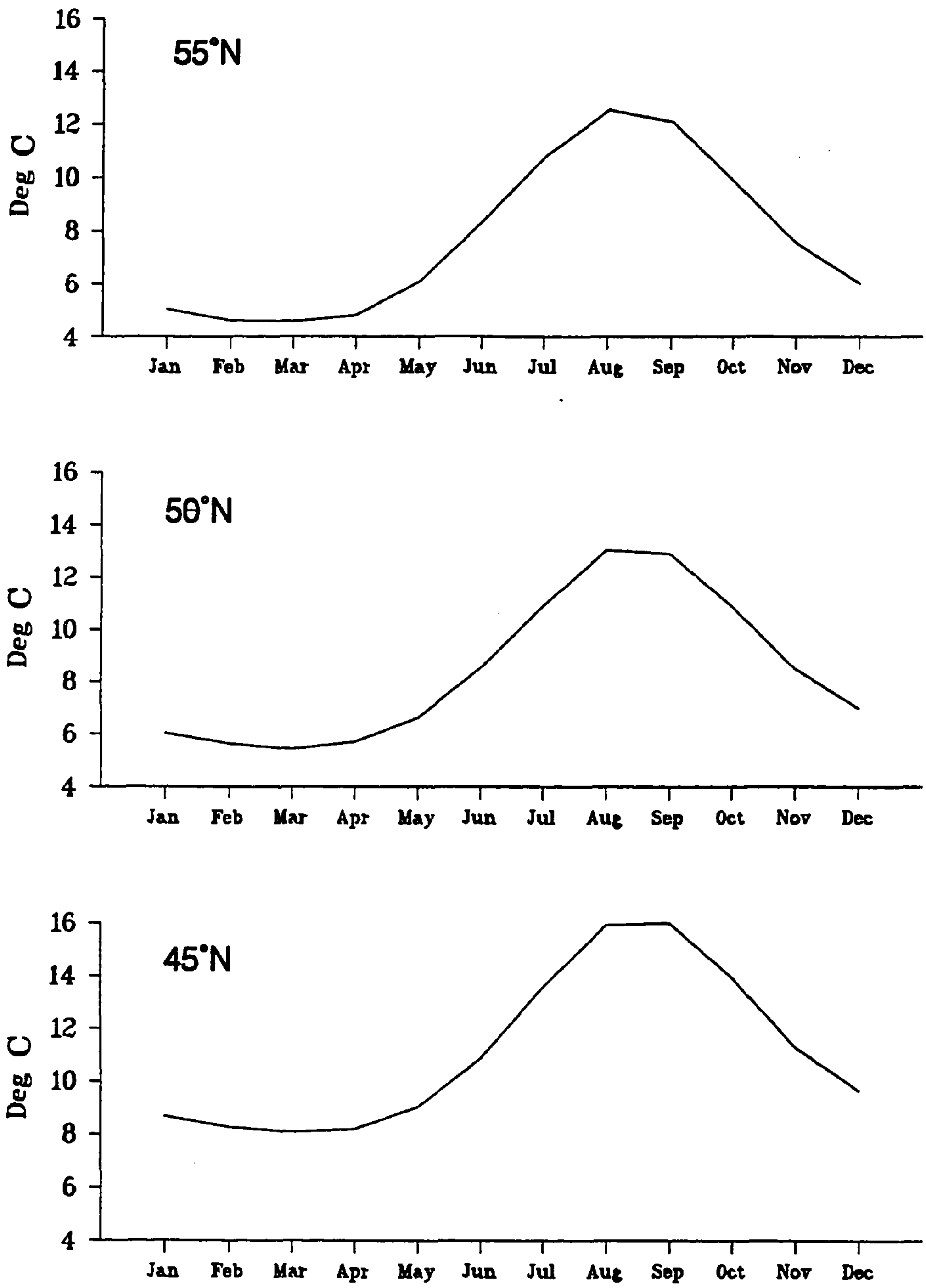


Figure 3.15. Seasonal cycles of mean monthly sea surface temperatures at 55°N, 50°N, and 45°N.

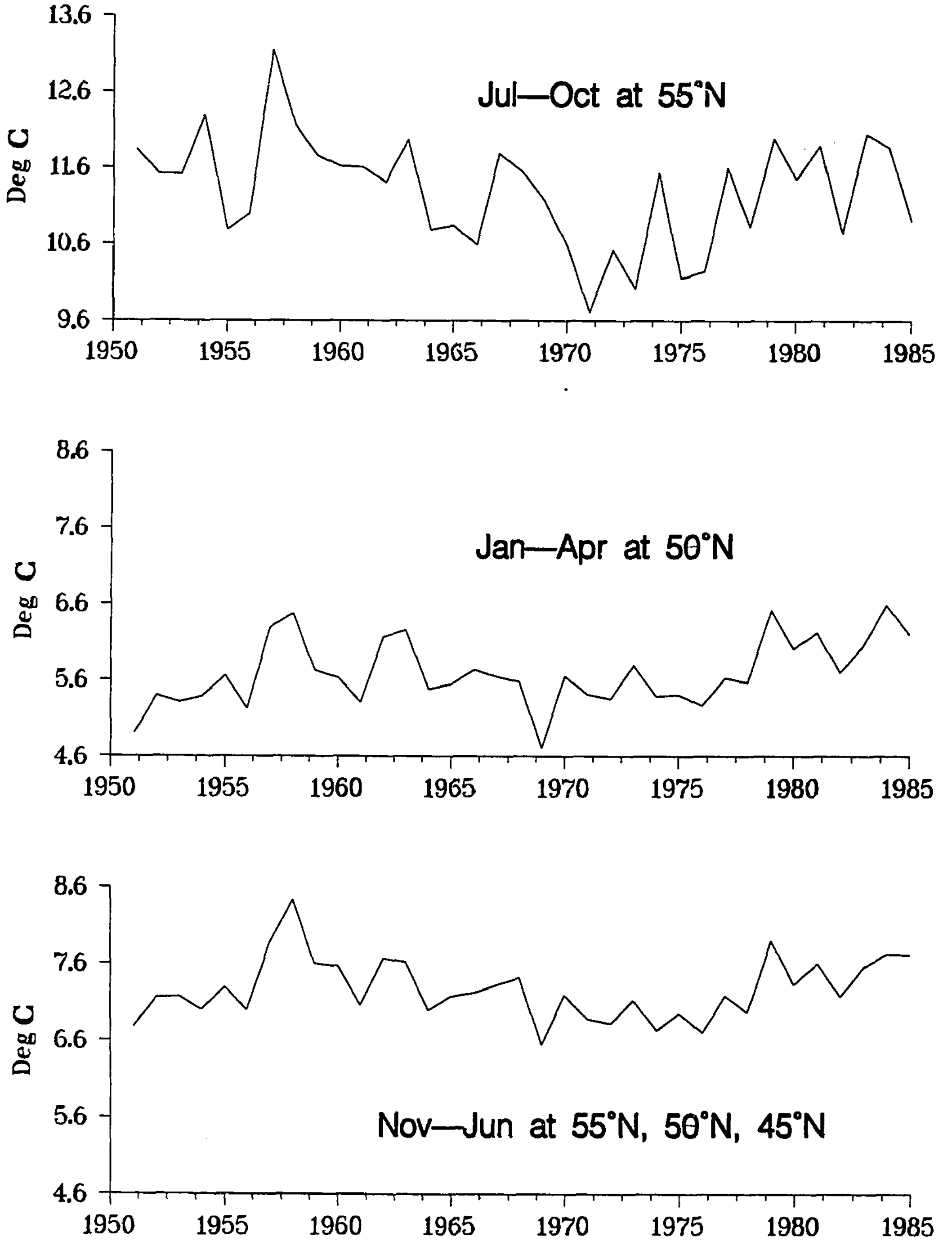


Figure 3.16. Mean of July through October sea surface temperatures at 55°N, January through April SST at 50°N, and November through June SST at 55°N, 50°N and 45°N.

Table 3.1. Time series of environmental variables compiled for Southeast Alaska. SSE, NSE, and SE are abbreviations for southern Southeast, northern Southeast, and Southeast Alaska, respectively.

Variable Abbrev.	n	Years Included	Variable Description
SSEcold	36	1950-1985	minimum 7-day air temp in SSE
SSEwint	75	1911-1985	mean of Dec-Feb air temp in SSE
NSEcold	36	1950-1985	minimum 7-day air temp in NSE
NSEwint	75	1911-1985	mean of Dec-Feb air temp in NSE
SEcold	36	1950-1985	minimum 7-day air temp in SE
SEwint	75	1911-1985	mean of Dec-Feb air temp in SE
SSEdis	55	1931-1985	mean of Sep-Oct discharges in SE
NSEdis	55	1931-1985	mean of Aug-Sep discharges in SE
SEdis	55	1931-1985	mean of Aug-Oct discharges in SE
SEcdis	55	1931-1985	mean of Oct-Nov discharges in SE
Lowsdis	55	1931-1985	smallest two-month average of discharges (Jun-Sept) in SE
SSEsst	64	1922-1985	mean of May-Jun SST in SSE
NSEsst	42	1944-1985	mean of May-Jun SST in NSE
SEsst	42	1944-1985	mean of May-Jun SST in SE
SEupw	40	1946-1985	mean of Jun-Jul upwelling (SE)
Nwind	40	1946-1985	mean of Aug-Oct wind near Seward
SST55s	35	1951-1985	mean of Jul-Oct SST at 55^{o}N
SST50w	35	1951-1985	mean of Jan-Apr SST at 50^{o}N
SSTave	35	1951-1985	mean of Nov-Jun SST at 45^{o},50^{o},55^{o}N

Table 3.2. Expected lag-relations between salmon catches and environmental time series for Southeast Alaska, assuming that pink salmon are 2, chum and coho salmon are 4, and sockeye salmon are 5 years old at date of catch. Codes: P = parents, E = eggs, J = juveniles, and M = maturing adults.

		Lag in Years Before Catch					
	Variable	0	1	2	3	4	5
	SEdis			P			
	SEcold		E				
P	SEwint		E				
I	SEsst		J				
N	SEupw		J				
K	Nwind		J				
	SST55s		J				
	SSTave	M					
	SEcdis					P	
	SEcold				E		
C	SEwint				E		
O	LOWsdis			J	J		
H	SEsst		J				
O	SEupw		J				
	Nwind		J				
	SST55s		J				
	SSTave	M					
	SEdis					P	
	SEcold				E		
C	SEwint				E		
H	SEsst				J		
U	SEupw				J		
M	Nwind				J		
	SST55s		M	M	J		
	SST50w	M	M	M			
S	SEdis						P
O	SEcold					E	
C	SEwint					E	
K	SEsst				J		
E	SEupw				J		
Y	Nwind				J		
E	SST55s		M	M	J		
	SST50w	M	M	M			

CHAPTER 4
UNIVARIATE TIME SERIES THEORY

Any set of time-sequenced observations is a time series. The series considered here are discrete, with observation intervals being evenly spaced over time. Theory and practices for the analysis of univariate series in the time domain are summarized in the classic text by Box and Jenkins (1976). In these stochastic forecasting models the value of a series at time t, Z_t, can be expressed by a mean and a linear combination of random shocks $\{a_t\}$,

$$Z_t = \mu + a_t + \psi_1 a_{t-1} + \psi_2 a_{t-2} + \dots \tag{4.1}$$

where the shocks are a sequence of uncorrelated random variables produced by a normal probability mechanism, $a_t \sim N(0,\sigma^2)$ and the sequence of ψ's are called psi weights. The observed series $Z_1, Z_2, \dots, Z_n$ is regarded as a sample realization from the stochastic process of interest. Since another set of observations generated by the process could be quite different, each observation Z_t is considered a random variable having probability $p[Z_t]$, and the series is considered an n-dimensional variable having probability $p[Z_1, Z_2, \dots, Z_n]$ (Box and Jenkins 1976). The generating process and the coefficients are unknown, and an empirical methodology is used to construct a model which characterizes the behavior of the observations.

4.1 Stationary Stochastic Processes

The assumption of stationarity characterizes the linear models considered in this analysis. Thus, means and variances of Z_t obtained from different realizations of the process are not a function of time and covariances are only a function of lag k:

$$\mu = E[Z_t] \qquad t = 1,..,n$$

$$Var[Z_t] = E[Z_t - \mu]^2 \qquad t = 1,..,n$$

$$Cov[Z_t, Z_{t-k}] = E[(Z_t - \mu)(Z_{t-k} - \mu)] \qquad k = \pm 1,2,..$$

$$Cov[Z_1, Z_{1+k}] = Cov[Z_2, Z_{2+k}] = \dots = Cov[Z_{n-k}, Z_n]$$

Under these conditions the covariance between variables of the sample series is called autocovariance, correlation between variables at lag k (called the autocorrelation) is

$$r_k = \frac{Cov[Z_t, Z_{t-k}]}{Var[Z_t]}$$

and a plot of r_k against lag k is called the sample autocorrelation function (SACF). Because correlations between two variables, say Z_t and Z_{t-2}, may be partly determined by the relationship each has with another variable, say Z_{t-1}, a partial autocorrelation function for each lag of interest in the series is usually calculated. Computer algorithms often calculate sample partial autocorrelations (SPACF) as the k^{th} partial coefficient in a multiple regression of Z_t against Z_{t-k} and k-1 backward lagged terms of Z_t (Abraham and Ledolter 1983). The variance associated with a sample autocorrelation coefficient is commonly estimated from an expression derived by Bartlett (1946) which assumes that if there are no correlations among variables more than q steps apart, and n is large,

$$Var[r_k] = \frac{1}{n}\left(1 + 2r_1^2 + \dots + 2r_q^2\right) \qquad k > q$$

The variances of estimated partial autocorrelation coefficients are approximately 1/n (Box and Jenkins 1976). The SACF and SPACF plotted with the estimates for 2 standard errors is the traditional tool, called a correlogram, used to "identify" the univariate time series process.

4.2 Stationary ARMA Models

Two important representations of the stationary linear stochastic model, (4.1), are the moving average (MA) and autoregressive (AR) forms. Integrated (I) models for nonstationary series are discussed in Section 4.4. Consider a model constructed from (4.1) by truncating the number of lag terms to 1 and letting $\tilde{Z}$ denote deviations from the mean ($\tilde{Z}_t = Z_t - \mu$). Let estimates of $\psi_i = -\theta_i$. Then, a simple model called the MA(1) model is

$$\tilde{Z} = a_t - \theta_1 a_{t-1} \qquad (4.2)$$

Further, define a linear operator B such that $B^k x_t = x_{t-k}$, x being any variable. Manipulating (4.2),

$$\tilde{Z}_t = (1 - \theta_1 B)a_t$$

$$(1 - \theta_1 B)^{-1} \tilde{Z}_t = a_t$$

$$(1 + \theta_1 B + \theta_1^2 B^2 + \theta_1^3 B^3 + \ldots)\tilde{Z}_t = a_t \tag{4.3}$$

shows that the model can also be expressed as an infinite sum of past values of $\tilde{Z}$, called an autoregressive model. When the values θ are restricted (as explained below), the series converges absolutely, the autoregressive model is stationary, and the moving average model is said to be invertible. The infinite series of left-hand side coefficients are called pi(π) weights (here $\pi_j = -\theta^j$), or the symbol ϕ_i is used when π_i is estimated in practice. The p^{th} order autoregressive model, AR(p), is thus

$$(1 - \phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p)\tilde{Z}_t = a_t$$

and the q^{th} order moving average model, MA(q), is

$$\tilde{Z}_t = a_t(1 - \theta_1 B - \theta_2 B^2 - \ldots - \theta_q B^q)$$

Both AR(p) and MA(q) terms can be used to denote autoregressive models with autocorrelated residuals. Thus

$$(1 - \phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p)\tilde{Z}_t = a_t(1 - \theta_1 B - \theta_2 B^2 - \ldots - \theta_q B^q) \tag{4.4}$$

is generally an ARMA(p,q) model. In practice, however, orders (p,q) rarely exceed 2, except as noted in Section 4.3.

Linear models of these types are stationary when ϕ_i assumes values within specific bounds. Box and Jenkins (1976) derived specific cases, for example:

$|\phi_1| < 1$ for the AR(1) model, and

$|\phi_2| < 1$,

$\phi_2 + \phi_1 < 1$,

$\phi_2 - \phi_1 < 1$ for the AR(2) model.

These formulae also define conditions for invertible MA(1) and MA(2) models if θ_i is substituted for ϕ_i. The coefficients of an MA polynomial are restricted to insure "invertibility" of an MA model to an equivalent (stationary) AR model. Stationarity and invertibility of the ARMA(1,1) model occur when both $|\phi_1|$ and $|\theta_1|$ are < 1.

4.3 Notation $(p,d,q)(P,D,Q)_s$

Many time series model forms can be described using the ARIMA(p,d,q) notation where p and q are the orders of AR(p) and MA(q) processes and d denotes the number of first degree differences taken to insure stationarity (Section 4.4). Thus ARIMA(p,0,q) denotes model (4.4). All terms of order less than p or q are implied unless postscripts such as $\phi_k = 0$ or $\theta_k = 0$ follow the (p,d,q) notation.

The notation is expanded for seasonal factors and multiplicative effects using the form $(p,d,q)(P,D,Q)_s$. The subscript s denotes a season (interval or cycle length) for the number of multiplicative terms P, Q. For example $(1,0,0)(1,0,0)_4$ and $(1,0,0)(0,0,2)_4$ denote the seasonal autoregressive (SAR) and seasonal moving average (SMA) models

$$(1-\phi_1 B)(1-\Phi_4 B^4)\tilde{Z}_t = a_t, \quad \text{and}$$

$$(1-\phi_1 B)\tilde{Z}_t = a_t(1-\Theta_4 B^4 - \Theta_8 B^8)$$

In econometric studies, s usually takes on values like 3 or 12 to denote quarterly or yearly seasonal trends in monthly data. In fisheries, s might signify generation length trends when annual data are used. Stationarity and invertibility conditions for multiplicative factors are determined by treating each factor separately (Pankratz 1983).

Shorthand notations are also used to denote ARIMA equations. The notation $\phi(B)\tilde{Z}_t = \theta(B)a_t$ refers to a general stationary ARMA model, and from equation (4.1), $\tilde{Z}_t = \psi(B)a_t$ shows how the current value of a series is related to $\{a_t\}$. Finally, the notation $\pi(B)\tilde{Z}_t = a_t$ shows how the current and past values of the series are related to the current shock, a_t.

4.4 Nonstationary ARIMA models

Nonstationarity in the variance or mean of a time series should be removed before building ARMA models. Variance heterogeneity in fisheries data is commonly removed by taking logarithms or square roots of the series. A square root transformation, for example, is appropriately applied to count data following a Poisson distribution if the standard deviation is proportional to the series level.

Homogeneous nonstationarity occurs when the mean of the series exhibits a time-changing level or trend. Many homogeneous nonstationary series can be made stationary and modeled as ARMA processes by taking successive differences of the series ∇Z_t, $\nabla^2 Z_t$, where $\nabla = (1 - B)$. When this operation is performed, Z_t becomes the sum of previous differences, or "integrated." The number of differences required to impose stationarity in the mean is **d** in the (p,**d**,q) notation. The differencing transformation is used to transform the polynomial component for a time changing mean μ_t, in d differencing operations, to a constant μ. Stationarity cannot be achieved for non-polynomial descriptions of μ_t, however, and only certain classes of error structures in the data admit a stationary error structure in ∇Z_t (van der Vaart 1978). Seasonal nonstationarity is modeled by differencing the data with lag s equal to the season or period length. The number of seasonal differences taken is **D** in the $(P,\mathbf{D},Q)_s$ notation. The notation $(p,0,q)(0,1,0)_4$ means that a trend with season = 4 was removed from the data by differencing.

4.5 Model Building

The heart of applied time series analysis is that the ACF and PACF for many sample data series are sufficiently distinct to identify orders of autoregressive and/or moving average polynomials that could describe the process that generated the series. Model building is an iterative process of identification, estimation, and diagnostic checking which concludes with a parsimonious model.

4.5.1 Preliminaries

Model building begins with plotting the series and checking the correlogram for patterns of obvious nonstationarity. Correlations near 1 or a slow linear decay in the SACF beginning at lag 1 positively indicate the need to difference the data. However, a slow linear decay in the SACF could begin at r_1 much lower than 1 (Wichern 1973; Box and Jenkins 1976) so that inspection of the correlogram does not provide quantitative evidence of nonstationarity in all cases. If the series is overdifferenced the variance may increase, the SACF will become more complicated, and models less parsimonious (Abraham and Ledolter 1983). Since overdifferencing a series can increase its variance, simply comparing $\mathrm{var}(Z_t)$ to $\mathrm{var}(\nabla Z_t)$ may be useful. Recent research (Tsay and Tiao 1984, 1985) suggests that the determination of homogeneous stationarity can be quantified during the model identification procedure.

4.5.2 Identification

Correlograms for autoregressive, moving average, or ARMA polynomials (Table 4.1) which are similar to the sample correlogram are identified. For example, if the

SPACF contains significant correlations only at lags 1 and 2 and the SACF exhibits a rapid or oscillatory decay, an AR(2) model is indicated. In contrast, if the autocorrelations are not different from 0 for all lags $k > q$ and the SPACF is dominated by decaying exponentials or sine waves, a MA(q) model is indicated. Time series generated by AR or MA processes of order 1 or 2 are often easy to identify, while correlograms indicating mixed ARMA(p,q) and seasonal processes may lead to several alternative hypotheses to be tested. In practice, the effects of sampling and other variability may also make identification difficult.

Numerous recent texts on time series analysis present ARMA correlograms and sample analysis (McCleary and Hay 1980; Abraham and Ledolter 1983; Pankratz 1983; Vandaele 1983; Wei 1990). In addition, new methods to aid in the identification of model parameters are available (Bequin et al. 1980; Tsay and Tiao 1984, 1985). Tsay and Tiao (1984) propose an Extended Sample Autocorrelation Function (ESACF) Table for identification of stationary and nonstationary series. The ESACF is a k (row) by j (col) matrix of autocorrelations $r_j(k)$, ($k=0,1,2,..$ $j=1,2,..$) where the row and column indices correspond to AR(p) and MA(q) orders, respectively. Correlations in the first row of the ESACF ($k=0$) are the SACF's of the original series, and in row $k>0$ they are the lag j autocorrelations of residual series, as explained in Tsay and Tiao (1984).

Tsay and Tiao show the p^{th} ESACF of an ARMA(p,q) process has the same "cutting off" property as the SACF of a pure MA process. A triangular pattern of zeros indicating the likely model is thus formed between significant and nonsignificant values of $r_j(k)$ in the ESACF Table. For example, an ESACF Table for an ARMA(2,1) process where significant and nonsignificant $r_j(k)$ are shown as X and O, respectively, is:

	MA						
AR	0	1	2	3	4	5	6
0	X	X	X	X	X	X	X
1	X	X	X	X	X	X	X
2	X	O	O	O	O	O	O
3	X	X	O	O	O	O	O
4	X	X	X	O	O	O	O
5	X	X	X	X	O	O	O
6	X	X	X	X	X	O	O

The nonsignificant (zero) at the left vertex of the triangle corresponds to the ARMA(p,q) order if the series is stationary, and to the ARIMA(p+d,q) order when the series is nonstationary. For example, the value of $| \phi_1 |$ estimated for an AR(1,1) model will be less than 1 if the series is stationary and will approach or exceed 1 if the series is nonstationary, indicating (1-B) is a factor in Z_t.

4.5.3 Estimation, Diagnostic Checking, and Model Validation

Estimation of model parameters by maximum likelihood and nonlinear least squares is desirable (Box and Jenkins 1976; Pankratz 1983). Backforecasting can be employed to make the estimation unconditional, e.g., to estimate the initial (unobserved) shocks. If an estimated model is stationary and/or invertible, a series of tests may be conducted to ensure model adequacy.

Recommended diagnostic tests include comparing parameter estimates against their standard errors and checking the residual series for serial and seasonal correlation. Serial correlation (i.e., correlation between successive random variables) is frequently tested by comparing a statistic (Q) derived from a sum of the autocorrelations of the residual series against critical values from a χ^2 distribution (Box and Pierce 1970; Ljung and Box 1978). Finally, underfitting and overfitting otherwise adequate models is done to insure model parsimony and completeness. The model building process is repeated as necessary to correct model deficiencies.

In some analyses several completely adequate alternate models may result from tentative identifications. Akaike (1974) developed a statistic (AIC) to aid selection between alternate ARMA models. The definition of AIC is derived from the maximum likelihood estimate of σ^2. Ozaki (1977) extended AIC to include both stationary and nonstationary (d=1,2,..) models. For the purpose of comparing models,

$$AIC = N \ln(\sigma^2) + \left(\frac{N}{N-d}\right)^2 2\,(p + q + 1 + \xi)$$

where N is sample size, $\xi = 1$ if $d = 0$, or $\xi = 0$ otherwise (Ozaki 1977). When several competing models exist, the minimum AIC denotes the better model. The value of using AIC to select between competing models derives from the penalty function for adding parameters to the model.

Model validation is important when forecasting is the primary goal. The traditional procedure calls for withholding recent data from the analysis, then forecasting the withheld data. Forecasts of the withheld data should be close, and forecast errors should be consistent with the variance of the residual series.

Table 4.1. Properties of the ACF and the PACF for various ARMA models (Abraham and Ledolter 1983, Table 5.3).

Model	ACF	PACF
$(1,d,0)$ AR(1)	Exponential or oscillatory decay	$\phi_{kk} = 0$ for $k > 1$
$(2,d,0)$ AR(2)	Exponential or sine wave decay	$\phi_{kk} = 0$ for $k > 2$
$(p,d,0)$ AR(p)	Exponential and/or sine wave decay	$\phi_{kk} = 0$ for $k > p$
$(0,d,1)$ MA(1)	Autocorrelation $r_k = 0$ for $k > 1$	Dominated by damped exponential
$(0,d,2)$ MA(2)	Autocorrelation $r_k = 0$ for $k > 2$	Dominated by damped exponential or sine wave
$(0,d,q)$ MA(q)	Autocorrelation $r_k = 0$ for $k > q$	Dominated by linear combination of damped exponentials &/or sine waves
$(1,d,1)$ ARMA(1,1)	Tails off. Exponential decay from lag 1	Tails off. Dominated by exponential decay from lag 1
(p,d,q) ARMA(p,q)	Tails off after q-p. Exponential and/or sine wave decay after q-p lags.	Tails off after p-q lags. Dominated by damped exponentials and/or sine waves after p-q lags.

CHAPTER 5
UNIVARIATE TIME SERIES MODELS

Univariate ARIMA models for catch, recruitment, and environmental time series are developed in this chapter. Models for catch are developed in numbers and biomass. Models for recruitment were made to see if recruitment was more forecastable than catch. If it was, it might be useful to forecast catch from a forecast of recruitment, by developing a relation between past recruitment and catch, or by reducing forecasts of recruitment by desired escapement. Finally, data for the environment was modeled for comparison to the fisheries data and to facilitate subsequent multivariate modeling.

5.1 Approach

A transformation to stabilize variance in each series was selected using the algorithm in AUTOBOX (Automatic Forecasting Systems 1984). Correlograms for each series were obtained in SYSTAT (Wilkinson 1988), and ESACF Tables were computed with an algorithm provided by Dr. Ruey Tsay (Tsay and Tiao 1984). Tentative identifications for each series were made from the correlograms and ESACF Tables. Acceptable model forms were determined by the procedures described in Chapter 4, using 2 standard errors (SE) to test significance of the estimated parameter coefficients and residual correlations. Parameter estimations were performed on a VAX 8600 computer with the BMDP P2T program (Dixon 1985) and the backcasting procedure.

Model stability and forecasting error for models of catch were estimated using a reverse data-withholding procedure. Five estimations and five one-step-ahead forecasts were made by sequentially deleting the last catch from the series, re-estimating model parameters, and making another forecast. If parameters were significant across the 5 estimations, a final estimation with the SCA program (Liu et al. 1986) was used to estimate parameter values by the conditional and "exact" likelihood functions for AR and MA parameters, respectively. The final estimation helped determine if model selection was dependent on the backcasting procedure. Also, the estimate of variance from the SCA program was used to calculate AIC (Ozaki 1977). Residual variance (RMS) is the residual sum of squares divided by N-p, where N is the number of observations after differencing and p is the highest AR lag in the model. RMS and AIC are reported for each model. Stability of the models for environmental data was evaluated as described above, but one-step-ahead forecasts were not made since this was not a goal of the study. The coefficient of determination (r^2) is reported for some models to provide an intuitive feel for the proportion of variance in a series which is explained by the model.

One-step-ahead forecast errors, $\varepsilon_t = \hat{Z}_t - Z_t$, are reported as percentages of the actual values, both with and without regard to sign:

$$PE = 100 \cdot \frac{\varepsilon_t}{Z_t} \quad \text{(percentage error)} \tag{5.1}$$

$$APE = 100 \cdot \frac{|\varepsilon_t|}{Z_t} \quad \text{(absolute percentage error)} \tag{5.2}$$

The mean PE (MPE) and APE (MAPE) were also calculated. MAPE, for example, is

$$MAPE = \frac{100}{n} \cdot \sum_{t=1}^{n} \frac{|\varepsilon_t|}{Z_t} \tag{5.3}$$

Median PE's and APE's are also reported. A mean or median PE measures bias while a mean or median APE reflects accuracy of the forecasts, given a new series (but the same model) each time. Parameter estimates, forecast and actual catches, and forecast errors are tabulated for one model in each fishing area. Values of RMS, MAPE, median APE, median PE, and AIC were considered when selecting this model, which usually was the model with lowest RMS and AIC. Note that forecasts resulting from the above procedure are not "true" forecasts since the model was identified using data to be forecast. True forecasting is examined in Chapter 11.

5.2 Models of Catch

5.2.1 Catch in Numbers

5.2.1.1 Even-Year Pink Salmon

Square root transformations were applied to the series of catches in southern (SSE), northern (NSE), and Southeast Alaska (SE) to stabilize variance. The correlograms (Figure C1) were all interpreted as realizations of AR(1) processes. ESACF Tables (Figure C2) also indicate that the AR(1) process is the likely model. Fitting the AR(1) model to each series reduced the residual series to white noise.

Overfitting an ARMA(1,0,1) model to the Southeast Alaska series also reduces the residual series to white noise, but the AR and MA parameters in the ARMA(1,0,1) are highly correlated (0.7) and the model is less parsimonious. Because MA(1) models were not obvious from the correlograms and AR(1) models satisfy all of the predetermined criteria, the modeling was terminated. The median absolute relative errors of the five most recent forecasts were 37% for southern Southeast, 97% for northern Southeast, and 44% for Southeast Alaska (Table 5.1).

5.2.1.2 Odd-Year Pink Salmon

Square root or logarithmic transformations were applied to the series of catches in each area (SSE, NSE, SE). AR(1) models were identified from correlograms (Figure C3) while ESACF Tables (Figure C2) indicate AR(1) or MA(1) processes. The AR(1) models were fitted to each series. Diagnostic procedures like those applied to the even-year series produced similar results so modeling was terminated. The median absolute relative errors of the five most recent forecasts were 43%, 13% and 46% for the catches in southern, northern, and Southeast Alaska, respectively (Table 5.2).

5.2.1.3 Combined-Years Pink Salmon

Models and forecasts of combined even- and odd-year pink salmon catch were constructed for comparison to the results for separate brood lines. Square root transformations were applied to the catches in each area (SSE, NSE, SE), and AR(2) models were found to describe the series. The values of RMS for the three AR(2) models were 0.1059, 0.0737, and 0.1347, respectively. The values of r^2 for the models in each area (SSE, NSE, SE) were 0.32, 0.30, and 0.35, respectively. Forecasts for 1981 through 1985 catches (Table 5.3) were at least as accurate as forecasts compiled from separate brood lines (Table 5.4). In general, the forecasts are biased low, and the largest deviations in the forecasts for southern Southeast Alaska catch (1983) and northern Southeast Alaska catch (1982 and 1984) occur in different years.

5.2.1.4 Chum Salmon

The autocorrelations (Figure C4) for the series of chum salmon catches in each area die out slowly and fall below the estimate of 2 standard errors at lag 7 (SSE and SE) and at lag 3 (NSE). The correlograms for the southern Southeast and Southeast series were not definitive with respect to stationarity, so tentative stationary and nonstationary identifications were made.

If the series for chum salmon are stationary, several different tentative identifications exist. The correlograms could suggest AR models with lag 1 and lag 4

Table 5.1. Parameter estimates, catch forecasts, actual catches, and relative errors of 5 forecasts from AR(1) models of square root transformed **even-year pink salmon** catches in southern Southeast (SSE), northern Southeast (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10*7.

	(pdq)(PDQ) Model Parameter Estimates (T-statistic)	yr	Forecast Catch			Actual Catch	Forecast Error	
	(1,0,0)		Lo 80% CI	Point	Up 80% CI		PE	APE
S	ϕ_1=.60	76	0.217	0.725	1.529	0.516	40.5	40.5
S	ϕ_1=.62	78	0.251	0.774	1.584	1.842	-58.0	58.0
E	ϕ_1=.57	80	0.795	1.640	2.789	1.291	27.1	27.1
	ϕ_1=.56	82	0.590	1.326	2.355	1.292	2.6	2.6
	ϕ_1=.56	84	0.600	1.325	2.334	2.090	-36.6	36.6
	ϕ_1=.56 (3.8)	86	0.911	1.773	2.918			
						medians	2.6	36.6
						means	-4.9	33.0
	(1,0,0)							
N	ϕ_1=.71	76	0.006	0.169	0.557	0.014	1076.3	1076.3
S	ϕ_1=.76	78	0.004	0.073	0.368	0.278	-73.7	73.7
E	ϕ_1=.72	80	0.071	0.361	0.875	0.143	152.7	152.7
	ϕ_1=.73	82	0.022	0.232	0.663	1.132	-79.5	79.5
	ϕ_1=.67	84	0.395	0.964	1.782	0.490	96.6	96.6
	ϕ_1=.65 (5.0)	86	0.143	0.535	1.175			
						medians	96.6	96.6
						means	234.5	295.8
	(1,0,0)							
S	ϕ_1=.70	76	0.211	0.821	1.830	0.533	54.1	54.1
E	ϕ_1=.72	78	0.218	0.822	1.814	2.124	-61.3	61.3
	ϕ_1=.66	80	0.988	2.086	3.589	1.448	44.1	44.1
	ϕ_1=.66	82	0.680	1.614	2.945	2.425	-33.5	33.5
	ϕ_1=.65	84	1.137	2.278	3.813	2.582	-11.8	11.8
	ϕ_1=.65 (4.8)	86	1.227	2.386	3.926			
						medians	-11.8	44.1
						means	-1.7	40.9

Table 5.2. Parameter estimates, catch forecasts, actual catches, and relative errors of 5 forecasts from AR(1) models of square root transformed **odd-year pink salmon** catches in southern Southeast (SSE), and log transformed catches in northern Southeast (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^7.

	(pdq)(PDQ) Model Parameter Estimates (T-statistic)	yr	Forecast Catch			Actual Catch	Forecast Error	
			Lo 80% CI	Point	Up 80% CI		PE	APE
	(1,0,0)							
S	ϕ_1=.51	77	0.085	0.647	1.733	1.124	-42.5	42.5
S	ϕ_1=.49	79	0.305	1.123	2.454	0.699	60.6	60.6
E	ϕ_1=.49	81	0.195	0.889	2.084	1.347	-34.0	34.0
	ϕ_1=.49	83	0.375	1.227	2.570	3.142	-60.9	60.9
	ϕ_1=.50	85	0.850	2.053	3.777	3.047	-32.6	32.6
	ϕ_1=.53 (3.6)	87	0.889	2.104	3.834			
						medians	-34.0	42.5
						means	-21.9	46.1
	(1,0,0)							
N	ϕ_1=.43	77	0.074	0.208	0.582	0.252	-17.6	17.6
S	ϕ_1=.41	79	0.142	0.391	1.075	0.383	2.1	2.1
E	ϕ_1=.41	81	0.172	0.464	1.254	0.536	-13.4	13.4
	ϕ_1=.41	83	0.202	0.536	1.423	0.605	-11.4	11.4
	ϕ_1=.41	85	0.216	0.565	1.478	2.050	-72.5	72.5
	ϕ_1=.42 (2.6)	87	0.363	0.978	2.636			
						medians	-13.4	13.4
						means	-22.6	23.4
	(1,0,0)							
S	ϕ_1=.53	77	0.299	0.746	1.864	1.384	-46.1	46.1
E	ϕ_1=.49	79	0.593	1.472	3.652	1.098	34.0	34.0
	ϕ_1=.49	81	0.532	1.303	3.189	1.897	-31.3	31.3
	ϕ_1=.48	83	0.709	1.717	4.159	3.750	-54.2	54.2
	ϕ_1=.49	85	1.009	2.457	5.984	5.099	-51.8	51.8
	ϕ_1=.53 (3.5)	87	1.242	3.032	7.399			
						medians	-46.1	46.1
						means	-29.9	43.5

Table 5.3. Parameter estimates, catch forecasts, actual catches, and relative errors of 5 forecasts from AR(2) models of square root transformed **pink salmon** catches in southern Southeast (SSE), northern Southeast (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^7.

	(pdq)(PDQ) Model Parameter Estimates (T-statistic)		yr	Forecast Catch			Actual Catch	Forecast Error	
	(2,0,0)	RMS=.1059		Lo 80% CI	Point	Up 80% CI		PE	APE
S	ϕ_1=.25	ϕ_2=.40	81	0.323	0.979	1.990	1.347	-27.3	27.3
S	ϕ_1=.25	ϕ_2=.40	82	0.490	1.252	2.365	1.292	-3.0	3.0
E	ϕ_1=.25	ϕ_2=.40	83	0.500	1.261	2.367	3.142	-59.9	59.9
	ϕ_1=.25	ϕ_2=.40	84	0.739	1.650	2.922	2.090	-21.1	21.1
	ϕ_1=.27	ϕ_2=.40	85	1.078	2.133	3.545	3.047	-30.0	30.0
	ϕ_1=.27 (2.4)	ϕ_2=.41 (3.7)	86	1.001	2.022	3.399			
							medians	-27.3	27.3
							means	-28.3	28.3
	(2,0,0)	RMS=.0737							
N	ϕ_1=.28	ϕ_2=.42	81	0.062	0.345	0.857	0.536	-35.6	35.6
S	ϕ_1=.27	ϕ_2=.42	82	0.064	0.347	0.856	1.132	-69.3	69.3
E	ϕ_1=.29	ϕ_2=.38	83	0.248	0.706	1.397	0.605	16.7	16.7
	ϕ_1=.28	ϕ_2=.39	84	0.298	0.783	1.499	0.490	59.8	59.8
	ϕ_1=.29	ϕ_2=.38	85	0.170	0.562	1.183	2.050	-72.6	72.6
	ϕ_1=.28 (2.4)	ϕ_2=.38 (3.3)	86	0.339	0.872	1.653			
							medians	-35.6	59.8
							means	-20.2	50.8
	(2,0,0)	RMS=.1347							
S	ϕ_1=.30	ϕ_2=.39	81	0.501	1.399	2.749	1.897	-26.2	26.2
E	ϕ_1=.30	ϕ_2=.39	82	0.685	1.690	3.141	2.425	-30.3	30.3
	ϕ_1=.30	ϕ_2=.38	83	0.913	2.033	3.596	3.750	-45.8	45.8
	ϕ_1=.31	ϕ_2=.38	84	1.319	2.630	4.390	2.582	1.9	1.9
	ϕ_1=.31	ϕ_2=.38	85	1.424	2.767	4.551	5.099	-45.7	45.7
	ϕ_1=.31 (2.7)	ϕ_2=.41 (3.6)	86	1.631	3.071	4.962			
							medians	-30.3	30.3
							means	-29.2	30.0

Table 5.4. Summary of forecasts, actual catches, and relative errors of forecasts from the AR(1) models of even- and odd-year pink salmon catches (from Tables 5.2 and 5.3) in the Alaska fishing areas. Catch in numbers/10^7.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.195	0.889	2.084	1.347	-34.0	34.0
82	0.590	1.326	2.355	1.292	2.7	2.7
83	0.375	1.227	2.570	3.142	-61.0	61.0
84	0.600	1.325	2.334	2.090	-36.6	36.6
85	0.850	2.053	3.777	3.047	-32.6	32.6
86	0.911	1.773	2.918			
				medians	-34.0	34.0
				means	-32.3	33.4

	Northern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.172	0.464	1.254	0.536	-13.4	13.4
82	0.022	0.232	0.663	1.132	-79.5	79.5
83	0.202	0.536	1.423	0.605	-11.4	11.4
84	0.395	0.964	1.782	0.490	96.7	96.7
85	0.216	0.565	1.478	2.050	-72.4	72.4
86	0.143	0.535	1.175			
				medians	-13.4	72.4
				means	-16.0	54.7

	Southeast Alaska Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.532	1.303	3.189	1.897	-31.3	31.3
82	0.680	1.614	2.945	2.425	-33.4	33.4
83	0.709	1.717	4.159	3.750	-54.2	54.2
84	1.137	2.278	3.813	2.582	-11.8	11.8
85	1.000	2.450	5.980	5.099	-51.9	51.9
86	1.227	2.386	3.926			
				medians	-33.4	33.4
				means	-36.5	36.5

components. The high correlations (to around lag 6) in the SACF of the southern Southeast and Southeast Alaska series might be interpreted as moving average components in an ARMA process, although the SPACF's look more "cut-off" than decaying. Because of this, seasonal autoregressive terms might be inferred from the correlograms. Thus, seasonal effects at lags 2 and 4 appear in the SPACF for the series of chum salmon catches in southern Southeast; in the series for northern Southeast seasonal correlations appear at lags 4 and 6; and in the series for Southeast Alaska they occur at 2, 4, and 6. Multiplicative autoregressive factors having these lags could also cause a slow decay in the SACF. Tentative identifications are thus AR models like (4,0,0) $\phi_{2,3}$=0 or $(1,0,0)(1,0,0)_4$, ARMA models like (1,0,4), and nonstationary models.

The ESACF Table for catches in southern Southeast Alaska (Figure C5) is clearly identified with p=1 and q=1. The ESACF Table for catches in northern Southeast Alaska does not clearly favor the p=1, q=4 identification over the p=1, q=0 model, so both models are possible. The ESACF Tables for catches in Southeast Alaska may indicate a AR model (p=1) with a seasonal moving average parameter (q=3) after example 4 in Tsay and Tiao (1984).

Southern Southeast

Three adequate models were found after all diagnostic checks were performed. The first model in Table 5.5 follows from the moving average identification, and the third model follows from the autoregressive identification. The second model results from the ESACF Table identification: parameter estimates for the (1,0,1) model are ϕ_1=0.96 and θ_1=0.69, so (1-B) is a possible factor of Z_t and the ARIMA model (0,1,1) is indicated (i.e., the original series is nonstationary). Forecasts for the (0,1,1) model are equivalent to forecasts from a simple exponential smoothing model (Box and Jenkins 1976). AIC favors the IMA(0,1,1) model.

Every model fit to the series overforecast the catches in 1981 and 1983 and underforecast the catches in 1982, 1984 and 1985. Forecasts from the ARMA(4,0,0) model, which had the lowest RMS and mean and median forecast errors, are shown on Table 5.6 (upper panel). The r^2 for this model was 0.46.

Northern Southeast

Three adequate models resulted from the identifications (Table 5.5, center panel). Forecasting the models revealed errors similar to those for the southern Southeast series: every model overforecast catch in 1981 and 1983, and underforecast catch in 1984 and 1985. AIC favors the two models with AR(1) parameters, which had r^2 values of 0.57.

Table 5.5. ARIMA models for **chum salmon** catch in Southeast Alaska fishing areas. Model parameters set equal to zero (par = 0), residual mean square error (RMS) and AIC of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each series.

Southern SE[a] (pdq),(PDQ)	par = 0	RMS	Median	Mean	MPE	AIC
(1,0,6)	$\theta_{1\text{-}3}, \theta_5$	.114	37.6	53.2	+23.8	-151
(0,1,1)		.110	38.3	44.9	-12.9	-159
(4,0,0)	ϕ_3	.106	25.4	43.3	+4.1	-156
Northern SE[a] (pdq),(PDQ)	**par = 0**	**RMS**	**Median**	**Mean**	**MPE**	**AIC**
(4,0,1)	$\phi_{1\text{-}3}$	.084	39.8	37.3	+8.7	-160
(1,0,0) $(1,0,0)_4$		.076	20.0	35.4	+8.9	-167
(1,0,4)	$\theta_{1\text{-}2}$	.075	27.7	44.6	+11.1	-167
Southeast Ak[a](pdq),(PDQ)	**par = 0**	**RMS**	**Median**	**Mean**	**MPE**	**AIC**
(0,1,3)	θ_2	.173	23.3	28.7	+3.0	-124
(4,0,1)	$\phi_{1\text{-}3}$	.172	46.4	43.7	+11.5	-122
(1,0,0) $(1,0,0)_4$		.158	41.8	43.3	+18.3	-129
(6,0,0) $(1,0,0)_1$	$\phi_{1\text{-}3}, \phi_5$	.134	18.6	29.0	-2.0	-139
(1,0,0) $(1,0,0)_4$ $(1,0,0)_6$		.115	20.3	31.9	+0.2	-150

[a] Square root transformed catch/10^6.

Table 5.6. Parameter estimates, catch forecasts, actual catches, and relative errors of 5 forecasts from models of square root transformed **chum salmon** catches in southern Southeast (SSE), northern Southeast (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^6.

	(pdq)(PDQ) Model Parameter Estimates (T-statistic)			yr	Forecast Catch Lo 80% CI	Forecast Catch Point	Forecast Catch Up 80% CI	Actual Catch	Forecast Error PE	Forecast Error APE
	$(4,0,0)\phi_3=0$									
S	$\phi_1=.35$	$\phi_2=.25$	$\phi_4=.26$	81	0.144	0.682	1.619	0.352	93.9	93.9
S	$\phi_1=.34$	$\phi_2=.26$	$\phi_4=.27$	82	0.151	0.694	1.632	0.840	-17.4	17.4
E	$\phi_1=.34$	$\phi_2=.26$	$\phi_4=.26$	83	0.129	0.640	1.540	0.514	24.5	24.5
	$\phi_1=.34$	$\phi_2=.27$	$\phi_4=.27$	84	0.219	0.820	1.806	1.831	-55.2	55.2
	$\phi_1=.32$	$\phi_2=.27$	$\phi_4=.26$	85	0.296	0.970	2.032	1.301	-25.4	25.4
	$\phi_1=.33$ (3.0)	$\phi_2=.26$ (2.2)	$\phi_4=.25$ (2.3)	86	0.541	1.376	2.594			
								medians	-17.4	25.4
								means	4.1	43.3
	$(1,0,0)(1,0,0)_4$									
N	$\phi_1=.72$	$\Phi_4=.29$		81	0.292	0.839	1.668	0.487	72.1	72.1
S	$\phi_1=.73$	$\Phi_4=.31$		82	0.164	0.608	1.331	0.513	18.6	18.6
E	$\phi_1=.73$	$\Phi_4=.31$		83	0.277	0.805	1.608	0.671	20.0	20.0
	$\phi_1=.73$	$\Phi_4=.31$		84	0.342	0.907	1.743	2.184	-58.5	58.5
	$\phi_1=.71$	$\Phi_4=.31$		85	0.936	1.802	2.948	1.954	-7.8	7.8
	$\phi_1=.72$ (9.6)	$\Phi_4=.31$ (2.9)		86	0.927	1.782	2.913			
								medians	18.6	20.0
								means	8.9	35.4
	$(1,0,0)(1,0,0)_4(1,0,0)_6$									
S	$\phi_1=.57$	$\Phi_4=.24$	$\Phi_6=.36$	81	0.500	1.360	2.641	0.850	60.1	60.1
E	$\phi_1=.57$	$\Phi_4=.25$	$\Phi_6=.37$	82	0.434	1.244	2.471	1.359	-8.5	8.5
	$\phi_1=.56$	$\Phi_4=.24$	$\Phi_6=.37$	83	0.558	1.439	2.730	1.196	20.3	20.3
	$\phi_1=.56$	$\Phi_4=.24$	$\Phi_6=.37$	84	0.698	1.650	3.004	4.047	-59.2	59.2
	$\phi_1=.56$	$\Phi_4=.26$	$\Phi_6=.35$	85	1.535	2.890	4.670	3.267	-11.5	11.5
	$\phi_1=.56$ (6.2)	$\Phi_4=.25$ (2.4)	$\Phi_6=.35$ (3.5)	86	1.754	3.176	5.017			
								medians	-8.5	20.3
								means	0.2	31.9

Parameter estimates and forecasts from the $(1,0,0)(1,0,0)_4$ model, which had the lowest mean and median forecast errors, are shown in Table 5.6 (center panel).

Southeast

All of the stationary models shown in the lower panel of Table 5.5 contain parameters for a season of four years and follow from additive or multiplicative forms of identifications made from the correlograms. The IMA(0,1,3) $\theta_2=0$ model follows from the ESACF Table identification: estimating the (1,0,3) model gives $\phi_1\approx1$, then that $\theta_2=0$. The multiplicative combination in the last model was discovered by trial and error. The signs of the forecast errors from all 5 models were the same in 3 of 5 years (1981, 1984, and 1985). Forecasts from the minimum-RMS and minimum-AIC model are shown in Table 5.6 (lower panel). The value of r^2 for this model was 0.64.

5.2.1.5 Sockeye Salmon

The autocorrelations for sockeye salmon catches in each area (Figure C6) exhibit a slow decay that indicates nonstationarity. The SACF and SPACF for the differenced series of southern and Southeast sockeye catches contain peaks at lag 2 but not lag 1. The ESACF Tables (Figure C7) identify models for catch in southern and Southeast Alaska by p=1, q=2; a model for northern Southeast Alaska is identified by p=1, q=0.

When ARMA models suggested by the ESACF Tables were fit to the series, estimates of $\phi_1=0.90$, $\phi_1=0.86$, and $\phi_1=0.93$ were obtained for southern, northern, and Southeast models, respectively. Thus, models having differencing operators were possibilities for these series. It was not possible to distinguish between (0,1,2) and (2,1,0) models for these differenced series. Analyses of the three residual series suggested only that a parameter for lag 6 be included in the model for catch in Southeast Alaska; AIC clearly favors the MA(2) form of this model (Table 5.7).

Mean and median forecast errors for the two models of catch in each area (Table 5.7) are nearly identical. However, MPE is relatively low for the (2,1,0) model in SSE and the (0,1,1) model in NSE. Forecasts from these two models, and the minimum-RMS and minimum-AIC model in SE Alaska, are shown in Table 5.8. One forecast from each series exceeds the 80 percent confidence interval for the forecast. Actual catches for 1982 and 1985 were above forecasts from all six models. The values of r^2 for the models in each area (SSE, NSE, SE) were 0.53, 0.73, and 0.76, respectively.

5.2.1.6 Coho Salmon

The autocorrelations for coho salmon catches in each area (SSE, NSE, SE) were different (Figure C8). Correlograms for the southern and Southeast series suggested both

Table 5.7. ARIMA models for **sockeye salmon** catch in Southeast Alaska fishing areas. Model parameters set equal to zero (par = 0), residual mean square error (RMS) and AIC of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each series.

Southern SE[a] (pdq),(PDQ)	par = 0	RMS	Median	Mean	MPE	AIC
(2,1,0)	ϕ_1	.172	25.0	24.1	-9.5	-128
(0,1,2)	θ_1	.170	24.9	27.1	-16.2	-129
Northern SE[a] (pdq),(PDQ)	**par = 0**	**RMS**	**Median**	**Mean**	**MPE**	**AIC**
(0,1,1)		.174	17.7	22.8	-15.7	-127
(0,1,2)		.159	21.7	21.8	-21.7	-132
Southeast Ak[b](pdq),(PDQ)	**par = 0**	**RMS**	**Median**	**Mean**	**MPE**	**AIC**
(0,1,6)	$\theta_1, \theta_{3\text{-}5}$	.024	21.3	21.4	-15.3	-274
(6,1,2)	$\phi_{1\text{-}5}, \theta_1$	.022	18.4	19.0	-14.5	-280

[a] Square root transformed catch/10^5.
[b] Square root transformed catch/10^6.

Table 5.8. Parameter estimates, catch forecasts, actual catches, and relative errors of 5 forecasts from models of square root transformed **sockeye salmon** catches in southern Southeast (SSE), northern Southeast (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^5 except SE series is numbers/10^6.

	(pdq)(PDQ) Model Parameter Estimates (T-statistic)	yr	Forecast Catch Lo 80% CI	Point	Up 80% CI	Actual Catch	Forecast Error PE	APE
	(2,1,0)ϕ_1=0							
S	ϕ_2=-.45	81	4.376	6.903	10.004	7.200	-4.1	4.1
S	ϕ_2=-.45	82	3.925	6.314	9.269	8.421	-25.0	25.0
E	ϕ_2=-.44	83	5.711	8.530	11.914	9.437	-9.6	9.6
	ϕ_2=-.44	84	5.991	8.851	12.267	6.476	36.7	36.7
	ϕ_2=-.45	85	3.765	6.092	8.976	11.117	-45.2	45.2
	ϕ_2=-.44 (-4.2)	86	9.154	12.716	16.862			
						medians	-9.6	25.0
						means	-9.5	24.1
	(0,1,1)							
N	θ_1=.40	81	1.037	2.469	4.513	2.099	17.7	17.7
S	θ_1=.40	82	0.900	2.244	4.192	4.389	-48.9	48.9
E	θ_1=.42	83	1.676	3.414	5.764	4.723	-27.7	27.7
	θ_1=.39	84	2.251	4.209	6.774	4.548	-7.5	7.5
	θ_1=.38	85	2.421	4.424	7.026	5.040	-12.2	12.2
	θ_1=.37 (3.4)	86	2.720	4.809	7.490			
						medians	-12.2	17.7
						means	-15.7	22.8
	(6,1,2)ϕ_{1-5}, θ_1=0							
S	ϕ_6=.34 θ_2=.46	81	0.437	0.735	1.110	1.080	-31.9	31.9
E	ϕ_6=.28 θ_2=.42	82	0.824	1.218	1.689	1.493	-18.4	18.4
	ϕ_6=.30 θ_2=.43	83	1.078	1.522	2.043	1.569	-3.0	3.0
	ϕ_6=.30 0_2=.42	84	0.928	1.340	1.827	1.204	11.3	11.3
	ϕ_6=.31 θ_2=.43	85	0.887	1.288	1.763	1.849	-30.4	30.4
	ϕ_6=.34 (3.2) θ_2=.42 (4.2)	86	1.433	1.938	2.519			
						medians	-18.4	18.4
						means	-14.5	19.0

stationary and nonstationary models. The series for northern Southeast Alaska was assumed to be white noise except for the weak peak at lag 7 in the SPACF. The ESACF Tables (Figure C9) suggested the (1,0,1) model for catches in southern and Southeast Alaska. The ESACF for the northern series was ambiguous.

Southern Southeast

Four models for coho salmon catches in southern Southeast Alaska were found (Table 5.9). The (1,0,4) model followed from the identification of moving average terms, and the (2,0,0) model from an autoregressive possibility. An autoregressive model with a multiplicative factor for lag 4 (model 3) was also found. The AR(2) model fit the data slightly better than the two other stationary models (Table 5.9). The (1,0,1) model identified from the ESACF Table was fit to the series, yielding an estimate of ϕ_1=0.93. Thus, (1-B) is a possible factor of Z_t and the IMA(0,1,1) model was estimated and found adequate.

The pattern of signed forecast errors was the same in all models: 1984 forecasts are greater than actual catches, and in all other years the actual catches are greater than the forecasts. Forecasts from the model which forecast recent data best, (1,0,4) $\theta_{1\text{-}3}$=0, are shown in Table 5.10. This model had an r^2 of 0.46.

Northern Southeast

The series of catches in northern Southeast Alaska was reduced to white noise with an SMA(7) model (Table 5.9, middle panel), which produced very poor, and low, forecasts of all five recent catches (Table 5.10, middle panel). The r^2 for this model was only 0.11. Adding an AR(1) parameter to this model would improve its performance, but the parameter estimate was not significant (±2 SE) when data were deleted from the series (1981-1985), so the parameter was not included in the current model.

Southeast

An ARMA(1,0,6) model for Southeast catches (Table 5.9, lower panel) resulted from the moving average model interpretation of the correlogram. When a (1,0,1) model is estimated for the series (the ESACF identification), ϕ_1=0.88, so a (0,1,1) model is possible.

Forecasts errors from the two models for this series were almost identical (Table 5.9, lower panel). RMS and AIC favor the stationary (1,0,6) model, which had an r^2 of 0.34. The IMA model underforecast all five catches of coho salmon in Southeast Alaska (1981-1985), and the (1,0,6) model underforecast all but the 1984 catch (Table 5.10, lower panel).

Table 5.9. ARIMA models for **coho salmon** catch in Southeast Alaska fishing areas. Model parameters set equal to zero (par = 0), residual mean square error (RMS) and AIC of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each series.

Southern SE[a] (pdq),(PDQ)	par = 0	RMS	Median	Mean	MPE	AIC
(1,0,4)	$\theta_{1\text{-}3}$	.297	11.8	18.4	-10.2	- 61
(0,1,1)		.286	23.4	25.3	-20.5	- 67
(1,0,0) $(1,0,0)_4$		.285	14.5	19.2	-13.6	- 64
(2,0,0)		.282	23.7	21.8	-12.3	- 64
Northern SE[b] (pdq),(PDQ)	**par = 0**	**RMS**	**Median**	**Mean**	**MPE**	**AIC**
(0,0,7)	$\theta_{1\text{-}6}$	.164	43.0	36.8	-36.8	- 99
Southeast Ak[c](pdq),(PDQ)	**par = 0**	**RMS**	**Median**	**Mean**	**MPE**	**AIC**
(0,1,1)		.109	28.2	28.4	-28.4	-147
(1,0,6)	$\theta_{1\text{-}5}$	.092	28.2	23.7	-23.4	-154

[a] Square root transformed catch/10^5.
[b] Log transformed catch/10^5.
[c] Log transformed catch/10^6.

Table 5.10. Parameter estimates, catch forecasts, actual catches, and relative errors of 5 forecasts from models of square root transformed **coho salmon** catches in southern Southeast (SSE), and log transformed catches in northern Southeast (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^5 except SE is numbers/10^6.

	(pdq)(PDQ) Model Parameter Estimates (T-statistic)		yr	Forecast Catch			Actual Catch	Forecast Error	
				Lo 80% CI	Point	Up 80% CI		PE	APE
	$(1,0,4)\theta_{1\text{-}3}=0$								
S	$\phi_1=.58$	$\theta_4=-.26$	81	2.856	5.945	10.152	6.408	-7.2	7.2
S	$\phi_1=.58$	$0_4=-.26$	82	3.804	7.242	11.778	8.216	-11.8	11.8
E	$\phi_1=.58$	$\theta_4=-.26$	83	4.175	7.713	12.329	8.662	-11.0	11.0
	$\phi_1=.58$	$\theta_4=-.26$	84	4.440	8.034	12.685	6.657	20.7	20.7
	$\phi_1=.58$	$\theta_4=-.26$	85	3.712	7.011	11.351	11.984	-41.5	41.5
	$\phi_1=.57$ (4.9)	$\theta_4=-.27$ (-2.0)	86	6.053	10.170	15.349			
							medians	-11.0	11.8
							means	-10.2	18.4
	$(0,0,7)\theta_{1\text{-}6}=0$								
N	$\theta_7=.36$		81	3.145	5.257	8.787	6.010	-12.5	12.5
S	$\theta_7=.36$		82	5.259	8.750	14.559	10.786	-18.9	18.9
E	$\theta_7=.40$		83	3.496	5.798	9.618	10.180	-43.0	43.0
	$\theta_7=.43$		84	3.276	5.462	9.107	10.832	-49.6	49.6
	$\theta_7=.43$		85	2.720	4.577	7.700	11.476	-60.1	60.1
	$\theta_7=.38$ (2.9)		86	2.908	4.979	8.524			
							medians	-43.0	43.0
							means	-36.8	36.8
	$(1,0,6)\theta_{1\text{-}5}=0$								
S	$\phi_1=.45$	$\theta_6=-.52$	81	0.593	0.888	1.330	1.407	-36.9	36.9
E	$\phi_1=.44$	$\theta_6=-.51$	82	1.020	1.534	2.307	2.138	-28.2	28.2
	$\phi_1=.47$	$\theta_6=-.54$	83	1.103	1.660	2.498	1.985	-16.4	16.4
	$\phi_1=.48$	$0_6=-.54$	84	1.287	1.933	2.902	1.920	0.6	0.6
	$\phi_1=.48$	$\theta_6=-.54$	85	1.081	1.618	2.422	2.540	-36.3	36.3
	$\phi_1=.49$ (4.4)	$\theta_6=-.54$ (-5.2)	86	1.121	1.684	2.529			
							medians	-28.2	28.2
							means	-23.4	23.7

Of the 7 models fit to the series of coho salmon catches in each area, the actual catches for 1981, 1982 and 1985 were greater than forecast catches in all 7 cases. Forecasts for 1983 and 1984, while mostly under the catch, depended on the area.

5.2.2 Catch in Weight

Correlograms for catch in weight (Figure C10) were compared to correlograms for catches in numbers (Figures C1-C4) and found to be functionally similar. Thus, initial identifications for the weight and number series were not substantially different. Because of this, the minimum mean square error model for each Southeast Alaska catch in numbers series was selected as a specific tentative identification for each series. These are AR(1) models for pink salmon, a multiple-season AR model for chum salmon, an ARMA model for coho salmon, and an ARIMA model for sockeye salmon.

Parameter estimates, parameter significance, and residual diagnostics for models of catch in weight were so similar to those for models of catch in numbers that estimation of other tentative model forms was not done. The final estimations, along with 5 forecasts from each model, are shown in Tables 5.11 and 5.12.

Large differences between relative errors in forecasting catch in weights and numbers were not apparent for most series (comparing statistics for SE Alaska in Tables 5.1 and 5.2 to Table 5.11, and comparing results in Tables 5.6, 5.8, and 5.10 to Table 5.12). However, recent catches of even-year pink salmon appear to be forecast more accurately when catch in weight is used instead of catch in numbers.

5.3 Models of Recruitment

Recruitment (catch plus escapement) of pink salmon to southern, northern, and Southeast Alaska (1960-1985) was estimated from indices of escapement and commercial catches in each area as described in Section 6.1. Correlation between catches (Tables A1-A3) and estimated escapements in SSE, NSE, and SE Alaska (1960-1985) is 0.88, 0.77, and 0.90, respectively. Thus, the catch and recruitment series are least similar in northern Southeast Alaska.

Models of square root transformed catches 1960-1985 were also constructed, so that forecasts from catch and recruitment series in each area could be compared. Square root transformations were used to stabilize variance of each series.

Correlograms and ESACF Tables suggest the recruitment series are stationary. However, the recruitment series for southern and Southeast Alaska, and possibly the series for northern Southeast Alaska, appear nonstationary (Figure 5.1). Comparing

Table 5.11. Parameter estimates, catch forecasts, actual catches, and relative errors of 5 forecasts from AR(1) models of square root transformed **even-year pink salmon catch biomass** (SE-EVEN) and log transformed **odd-year pink salmon catch biomass** (SE-ODD) in the Southeast Alaska fishing area. Catch in lbs/10^7.

	(pdq)(PDQ) Model Parameter Estimates (T-statistic)		Forecast Catch				Forecast Error	
	(1,0,0)	yr	Lo 80% CI	Point	Up 80% CI	Actual Catch	PE	APE
S	ϕ_1=.79	76	0.742	2.811	6.209	2.335	20.4	20.4
E	ϕ_1=.80	78	0.943	3.138	6.614	6.777	-53.7	53.7
-	ϕ_1=.76	80	3.435	7.090	12.055	5.632	25.9	25.9
E	ϕ_1=.76	82	2.829	6.149	10.742	7.946	-22.6	22.6
V	ϕ_1=.75	84	4.156	7.993	13.073	8.845	-9.6	9.6
E	ϕ_1=.75 (6.5)	86	4.714	8.690	13.874		——	——
N						medians	-9.6	22.6
						means	-7.9	26.4
	(1,0,0)							
S	ϕ_1=.61	77	1.116	2.701	6.539	6.789	-60.2	60.2
E	ϕ_1=.54	79	2.789	6.810	16.627	4.326	57.4	57.4
-	ϕ_1=.54	81	2.181	5.271	12.739	8.078	-34.8	34.8
O	ϕ_1=.53	83	3.113	7.457	17.866	11.713	-36.3	36.3
D	ϕ_1=.54	85	3.875	9.221	21.942	16.550	-44.3	44.3
D	ϕ_1=.55 (3.8)	87	4.823	11.444	27.158		——	——
						medians	-36.3	44.3
						means	-23.6	46.6

Table 5.12. Parameter estimates, catch forecasts, actual catches, and relative errors of 5 forecasts from models of square root transformed **chum** (SE-CHUM) and **sockeye** (SE-SOCK), and log transformed **coho** (SE-COHO)[a] salmon **catch biomass** in the Southeast Alaska fishing area. Catch in lbs/10^6 except chum in lbs/10^7.

	(pdq)(PDQ) Model Parameter Estimates (T-statistic)			yr	Forecast Catch Lo 80% CI	Point	Up 80% CI	Actual Catch	Forecast Error PE	APE
	$(1,0,0)(1,0,0)_4(1,0,0)_6$									
S	ϕ_1=.50	Φ_4=.20	Φ_6=.35	81	0.512	1.308	2.470	0.838	56.1	56.1
E	ϕ_1=.50	Φ_4=.21	Φ_6=.37	82	0.481	1.253	2.388	1.338	-6.3	6.3
-	ϕ_1=.50	Φ_4=.21	Φ_6=.37	83	0.556	1.363	2.527	1.070	27.5	27.5
C	ϕ_1=.50	Φ_4=.21	Φ_6=.37	84	0.630	1.470	2.660	3.830	-61.6	61.6
H	ϕ_1=.49	Φ_4=.23	Φ_6=.34	85	1.373	2.574	4.151	2.956	-12.9	12.9
U	ϕ_1=.50 (5.3)	Φ_4=.22 (2.1)	Φ_6=.34 (3.3)	86	1.536	2.787	4.407			
M										
								medians	-6.3	27.5
								means	0.6	32.9
	$(1,0,6)\theta_{1-5}$=0									
S	ϕ_1=.49	0_6=-.44		81	4.601	7.116	11.006	11.067	-35.7	35.7
E	ϕ_1=.47	θ_6=-.43		82	7.913	12.269	19.021	16.265	-24.6	24.6
-	ϕ_1=.48	θ_6=-.44		83	9.138	14.154	21.923	14.424	-1.9	1.9
C	ϕ_1=.49	θ_6=-.44		84	8.993	13.878	21.416	17.049	-18.6	18.6
O	ϕ_1=.49	θ_6=-.45		85	8.893	13.697	21.097	21.408	-36.0	36.0
H	ϕ_1=.51 (4.6)	θ_6=-.45 (-4.1)		86	9.386	14.495	22.387			
O										
								medians	-24.6	24.6
								means	-23.4	23.4
	$(6,1,2)\phi_{1-5}$=0, θ_1=0									
S	ϕ_6=.35	θ_2=.44		81	2.559	4.574	7.169	6.629	-31.0	31.0
E	ϕ_6=.30	θ_2=.41		82	5.028	7.725	11.000	10.040	-23.1	23.1
-	ϕ_6=.33	θ_2=.42		83	7.352	10.555	14.335	9.549	10.5	10.5
S	ϕ_6=.32	θ_2=.42		84	5.044	7.725	10.975	7.482	3.2	3.2
O	ϕ_6=.33	0_2=.43		85	5.660	8.460	11.820	11.512	-26.5	26.5
C	ϕ_6=.35 (3.4)	θ_2=.43 (4.3)		86	8.360	11.717	15.640			
K										
								medians	-23.1	23.1
								means	-13.4	18.9

a Coho catch estimated with catch taken by troll gear converted to round weight.

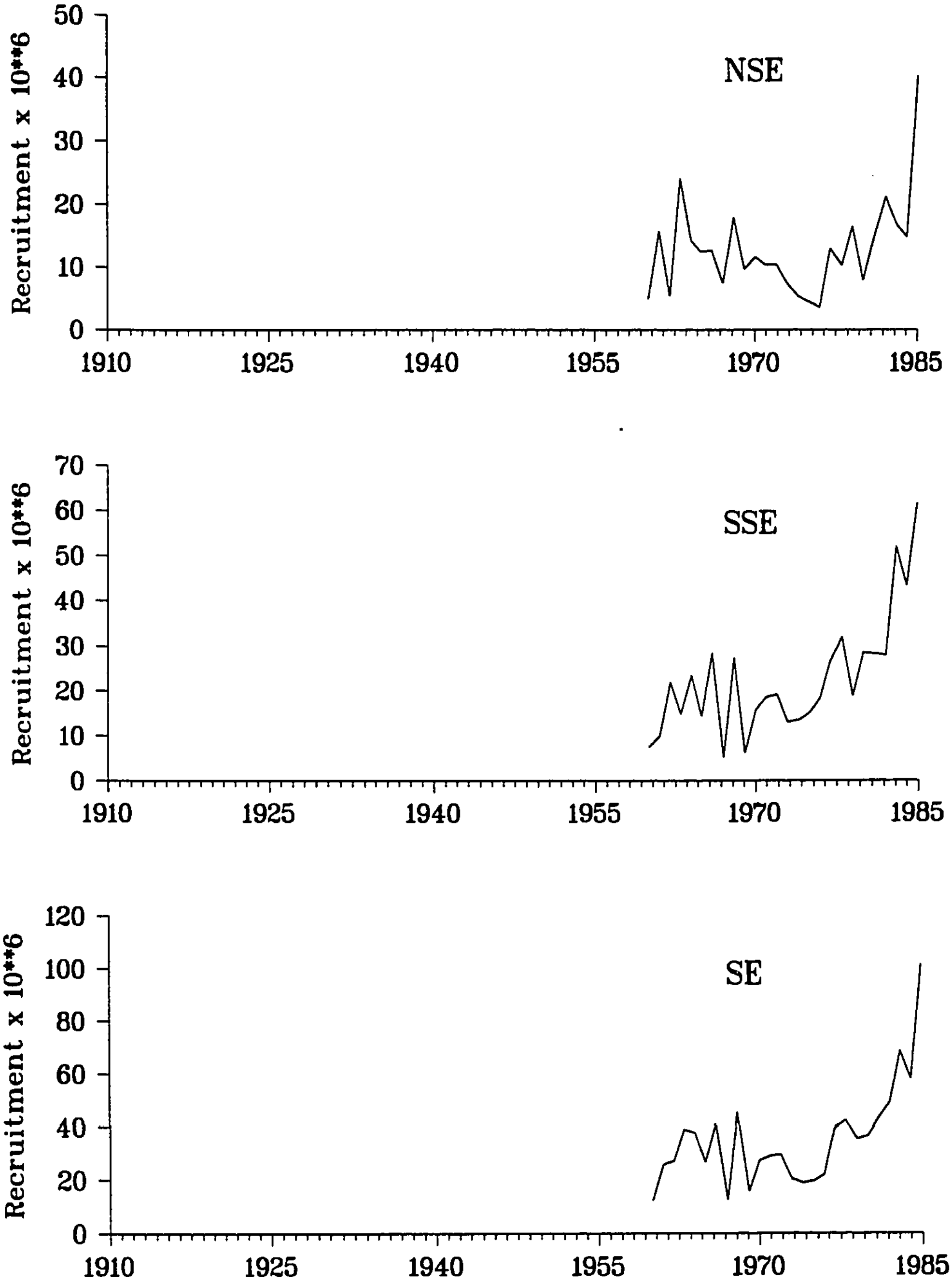


Figure 5.1. Estimates of pink salmon recruitment to northern (NSE), southern (SSE), and Southeast (SE) Alaska.

variances of each series before and after taking first differences (see Section 4.5.1) supports the judgement from viewing the plots: variances dropped 31% in SSE, dropped 22% in SE, but increased 29% in NSE, after taking differences. Thus, nonstationary models for recruitment and catch in each area, and stationary models for recruitment and catch in NSE were made for comparison.

Correlograms and ESACF Tables for first differences of the recruitment series (∇Z_t) in each area suggested ARIMA(1,1,0) models. The (1,1,0) model was thus fit to each series, and diagnostic testing yielded no inadequacies. Autocorrelations of recruitment (Z_t) in northern Southeast Alaska were not significant (±2 SE), but suggested an AR(2) model. The AR(2) model was therefore fit to the series for NSE Alaska; the parameter ϕ_1 was not significant (±2 SE) and was set to 0.

Stationary and nonstationary identifications for the short catch series were made to permit comparisons between the catch and recruitment series. Identification of ARMA(1,1,0) models for catches in each area and an AR(2) ϕ_1=0 model for catch in NSE Alaska were made from the plots (Figure 2.1), correlograms, and ESACF Tables as described above. The models showed no inadequacies.

RMS and AIC, and forecast statistics for each model of recruitment and catch in each area are shown in Table 5.13. The best model for the recruitment in NSE Alaska is clearly the ARIMA(1,1,0) model. The best model for the short series of catches in NSE Alaska is not as clear. Average and median forecast errors from the models of catch and recruitment in southern Southeast Alaska are similar. In contrast, the yearly and the average (or median) forecast errors from model of recruitment in Southeast Alaska are consistently below forecast errors from the model of catch.

5.4 Discussion of Models for Catch and Recruitment

The long-term series of catches are not clearly stationary, and varied ARIMA models were made to forecast the series. Square root and logarithmic transformations are needed to stabilize variance in the series. Simple AR(1) models describe odd- and even-year pink salmon catches. When brood lines of pink salmon (1915-1985) were combined, AR(2) models yielded forecasts at least as accurate as the models for separate brood lines. The AR(2) model also forecast the short-term series of catches (1960-1985) in northern Southeast Alaska at least as well as the ARMA(1,1,0) model (Table 5.13).

Models of pink salmon recruitment 1960-1985 were also constructed. Forecasts of each series (1981-1985) were biased low, as were the forecasts of catch. Catch and

Table 5.13. ARIMA models for **pink salmon recruitment** and catch in Southeast Alaska fishing areas, 1960-1985. Model parameters set equal to zero (par = 0), residual mean square error (RMS) and AIC of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each series.

Southern SE[a] (pdq),(PDQ)		par = 0	RMS	Median	Mean	MPE	AIC
(1,1,0)	recruitment		.089	24.3	23.6	-22.9	-58.7
(1,1,0)	catch		.097	20.2	24.9	-24.5	-56.6
Northern SE[a] (pdq),(PDQ)		**par = 0**	**RMS**	**Median**	**Mean**	**MPE**	**AIC**
(2,0,0)	recruitment	ϕ_1	.074	24.1	32.9	-32.9	-61.8
(2,0,0)	catch	ϕ_1	.078	32.9	47.2	-38.0	-60.2
(1,1,0)	recruitment		.076	34.4	31.2	-17.4	-62.7
(1,1,0)	catch		.084	72.4	61.1	-16.9	-60.3
Southeast Ak[a](pdq),(PDQ)		**par = 0**	**RMS**	**Median**	**Mean**	**MPE**	**AIC**
(1,1,0)	recruitment		.107	21.4	23.0	-23.0	-53.7
(1,1,0)	catch		.105	35.9	32.6	-29.0	-54.4

[a] Square root transformed recruitment or catch/10^7.

recruitment in SSE Alaska are forecast with similar accuracy and precision, 1981-1985. In NSE and SE Alaska, recruitment was forecast better than catch (Table 5.13). Forecasts of catch made from forecasts of recruitment are considered in Chapter 11.

An important result is the high degree of similarity between the forecast errors for pink salmon catch *and* recruitment from *different* time series models. Deviations from forecast and actual values in the series are so large (1981-1985) that every model considered during the analysis produced a similar result when viewed from a perspective wider than just comparing the summary statistics derived from the forecasts (Figure 5.2). Forecast errors in southern and northern Southeast Alaska also tended to oppose each other, and become smaller in the models for Southeast Alaska. Whether this is a characteristic of the fisheries or the aggregation of data could be important.

A significant effort was made to consider data other than catch in numbers. To this end, series and models for catch biomass in were constructed. However, models for landed catch were similar to those for catch in numbers, suggesting that both series contain the same amount of information useful for forecasting.

ARIMA models for chum and pink salmon catches produced the largest relative forecast errors for the period 1981 through 1985. The "best" forecasting models of pink salmon catch (Tables 5.3 and 5.13) yielded an average relative forecast error (MAPE) of 36% (SD=11%, n=6). Similarly, an average MAPE for the best forecasting chum salmon series (Table 5.6) was 37% (SD=5%, n=3). In contrast, the average MAPE for sockeye salmon was 23% (SD=3%, n=6, Table 5.7) and an average for coho salmon was 25% (SD=6%, n=7, Table 5.9). Relative errors in forecasting the pink, chum, coho, sockeye salmon series (1981-1985) do not follow the same pattern (Figure 5.3).

Univariate time series analysis provides a robust, relatively uncomplicated method of modeling salmon catches. However, forecast errors in a particular year can be quite high. Other methods for forecasting the series are presented in Chapters 6, 8, and 10.

5.5 Models of Environment

Correlograms (Figures C11-C16) of the 19 series are unlike those for the catch data. Only two of the series (SST50w and SSTave) are autocorrelated (±2 SE) at lag 1. All of the series are stationary as indicated by low values of the first several autocorrelations, but a type of seasonality or cyclic behavior is evident in many series. Eight of the 19 correlograms contain no significant autocorrelations (±2 SE), suggesting these series (SSEdis, SEdis, SEcdis, Lowsdis, SEupw, Nwind, NSEsst, SEsst) are white

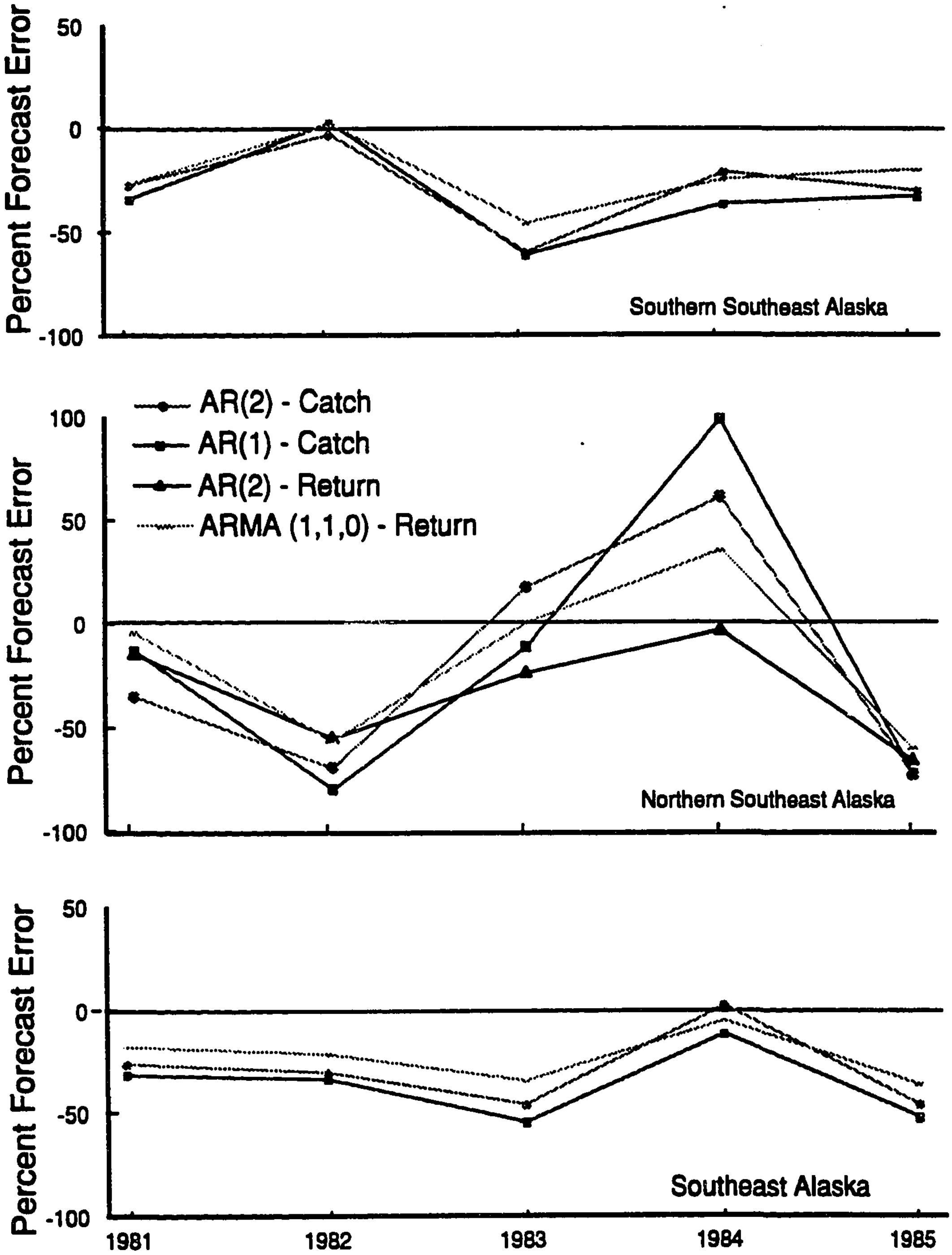


Figure 5.2. Percent forecast error for ARMA models of pink salmon catch and return in southern, northern, and Southeast Alaska. Except for the AR(1) model, all forecast errors are from models of data for both brood lines combined.

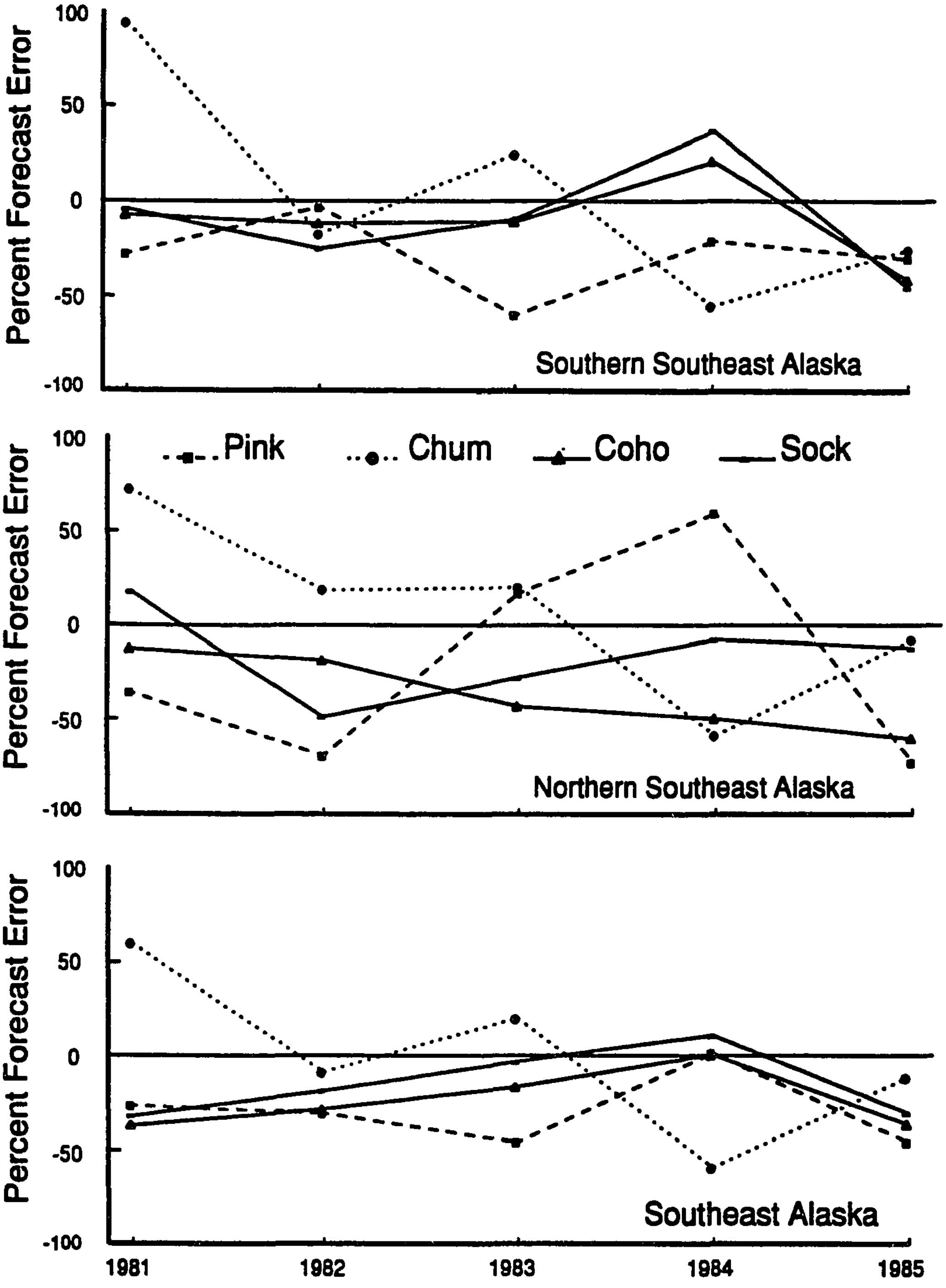


Figure 5.3. Percent forecast error for ARMA models of salmon catch in southern, northern, and Southeast Alaska, 1981-1985. Forecasts are from Table 5.3 (pink salmon), Table 5.6 (chum salmon), Table 5.8 (sockeye salmon), and Table 5.10 (coho salmon).

noise for the purposes of this study. However, autocorrelations in the SSEdis, NSEsst, and SEsst series were nearly significant and were modeled. Most significant seasonal autocorrelations occur at or near lags 8, 11, 5 and 3. ESACF Tables for all series were computed to order 5, but were not suggestive of low-order models and are not shown.

Negative (-) correlations around lags 8 and 11 in the air temperature and SST series (Figures C11, C12, C15, C16) suggest that low frequency cycles may be present. These correlations are most pronounced in the air temperature series, and weak positive (+) correlations occur at lags 16 and 22 in several correlograms. Since strong irregular periodicity occurs in annual temperatures (at about 15-22 years for air temperature, Chapter 3) the general patterns observed in these correlograms were not unexpected.

5.5.1 Low Winter Air Temperature

The SSEcold series will be used to illustrate analysis of the air temperature data. Evidence that seasonal differencing was appropriate was unconvincing (Figure C11); models with parameters for lag 1 and/or lag 8 were then considered. Parameter estimates for tentative AR(1), SAR(8), and SMA(8) models were significant across 5 data deletions, and the SAR(8) model fit the data best. However, high correlations remained in the residuals from each model. Also, parameters for lag 1 and lag 8 were not significant (±2 SE) when they appeared in the same model. Residuals from the SAR(8) model were most highly autocorrelated at lags 5, 11, and 12. Parameters for lags 5 and 11 were then combined with the parameter for lag 8 in various models. Models with 2 seasonal AR parameters and models with both seasonal AR and seasonal MA parameters were usually unstable when data was deleted from the model. Models with multiple SMA parameters did yield significant parameter estimates (Table 5.14, top panel) but yielded another diagnostic warning (invertibility) as noted below.

The model $(1-\phi B^{8})\tilde{Z}_t = (1-\theta B^{11})a_t$ for SSEcold, for example, was strongly influenced by the estimation method: the SMA(11) parameter was non-invertible using the likelihood algorithm in the SCA program, but was 0.33 using the backcasting algorithm in the BMDP program. Also, the two SMA models in Table 5.14 (top panel) were non-invertible ($\Sigma\theta \geq 1.0$) in at least 1 of 5 estimations in which data was deleted from the series and parameters re-estimated.

Results for the NSEcold and SEcold series were similar to those for SSEcold; two-parameter models were unstable or non-invertible, and are not shown (Table 5.14, middle and lower panels). In addition, the last observation (1985) in the NSEcold and SEcold series added instability to the models, abruptly affecting parameter estimates.

Table 5.14. Tentative ARMA models for **low (7-day minimum) winter air temperatures** in southern, northern, and Southeast Alaska. T-statistics (below parameter estimates), residual mean square errors (RMS), Akaike Criteria (AIC), and r^2 are shown for each series (n=36).

SSEcold (pdq),(PDQ)	RMS	AIC	r^2
$\tilde{Z}_t = (1 - \underset{(4.1)}{.47} B^5 - \underset{(4.6)}{.48} B^8)\, a_t$	22.0	119.	28.4
$(1 + \underset{(3.4)}{.50} B^8)\tilde{Z}_t = a_t$	20.7	115.	32.5
$\tilde{Z}_t = (1 - \underset{(3.6)}{.40} B^8 - \underset{(5.2)}{.57} B^{11})\, a_t$	19.0	114.	38.1
NSEcold (pdq),(PDQ)	**RMS**	**AIC**	**r^2**
$(1 + \underset{(3.1)}{.49} B^8)\tilde{Z}_t = a_t$	38.9	138.	20.7
SEcold (pdq),(PDQ)	**RMS**	**AIC**	**r^2**
$(1 + \underset{(3.4)}{.51} B^8)\tilde{Z}_t = a_t$	26.2	124.	28.0

In summary, diagnostics on the multi-parameter models were poor, and the SAR(8) model was selected as the most robust for these data. The SAR(8) models accounted for 21% to 33% of the variation in these series.

5.5.2 Mean Winter Air Temperature

Correlograms for mean winter air temperatures (Figure C12) are similar to those for low winter air temperatures, except correlations in the mean winter data appear somewhat stronger around lags 11 and 22. Again, however, seasonal differencing of the data seems unjustified. In spite of the relatively large sample size (n=75), low order AR or MA decay patterns were not obvious in the correlograms. Therefore, SAR and SMA identifications were pursued as in the analysis above (Section 5.5.1).

The identified models (Table 5.15) are similar to the models for the low temperatures series, and account for little (12%-28%) variation in the data. Compared to the previous analysis (Section 5.5.1) with smaller samples (n=36), instability and invertibility problems were much reduced with these data.

The last model in each panel of Table 5.15 had parameters that were not significant (±2 SE) when the likelihood algorithm in the SCA program was used. Thus, the upper model in each panel may be more robust. Even so, significant residual correlations remained at lag 7 from the SMA model for SSEwint, and at lag 11 from the SMA model for SEwint.

5.5.3 Freshwater Discharge, Upwelling, and Wind Speed

Correlograms for these series do not have strong seasonal correlations above lag 6 (Figures C13-C14) like those found in the correlograms for the air temperatures. Several of the freshwater discharge series (SEdis, SEcdis, Lowsdis), the upwelling series (SEupw), and wind speed series (Nwind) were assumed to follow white noise models because the correlations in the series were so weak. Models for freshwater discharge in southern (SSEdis) and northern (NSEdis) Southeast Alaska were constructed to account for the correlations in the ACF and PACF at low lags (Table 5.16). Nine percent of the variability in NSEdis was explained with a one parameter model, and 18% of the variability in the SSEdis was explained with a 2 parameter model. Residuals from these models were white noise.

5.5.4 Inland Sea Surface Temperature

The SST series for Ketchikan (SSEsst) contains a significant partial autocorrelation at lag 7 and nearly significant correlations at lags 4 and 6 (Figure C15). A 3 parameter (lags 4,6,7) autoregressive model for SSEsst (Table 5.17, upper panel)

Table 5.15. Tentative ARMA models for **mean winter (Dec-Feb) air temperatures** in southern, northern, and Southeast Alaska. T-statistics (below parameter estimates), residual mean square errors (RMS), Akaike Criteria (AIC), and r^2 are shown for each series (n=75).

SSEwint (pdq),(PDQ)	RMS	AIC	r^2
$\tilde{Z}_t = (1 - \underset{(5.3)}{.45}\, B^8 - \underset{(4.8)}{.40}\, B^{11})\, a_t$	8.82	171.	12.3
$(1 + \underset{(1.9)}{.20}\, B^8)\tilde{Z}_t = (1 - \underset{(4.2)}{.34}\, B^{11} - \underset{(6.5)}{.50}\, B^{12})\, a_t$	7.24	158.	28.0

NSEwint (pdq),(PDQ)	RMS	AIC	r^2
$\tilde{Z}_t = (1 - \underset{(4.9)}{.43}\, B^8 - \underset{(4.7)}{.40}\, B^{12})\, a_t$	11.8	193.	16.3
$(1 + \underset{(2.9)}{.33}\, B^8)\tilde{Z}_t = (1 - \underset{(3.3)}{.31}\, B^{12} + \underset{(5.7)}{.51}\, B^{13})\, a_t$	11.0	190.	22.3

SEwint (pdq),(PDQ)	RMS	AIC	r^2
$\tilde{Z}_t = (1 - \underset{(4.3)}{.40}\, B^8 - \underset{(3.9)}{.36}\, B^{12})\, a_t$	8.80	171.	19.3
$(1 + \underset{(3.1)}{.34}\, B^8)\tilde{Z}_t = (1 - \underset{(3.4)}{.30}\, B^{11} - \underset{(5.8)}{.49}\, B^{12})\, a_t$	8.18	168.	25.0

Table 5.16. Tentative ARMA models for seasonal **freshwater discharges** into Southeast Alaska. T-statistics (below parameter estimates), residual mean square errors (RMS), Akaike Criteria (AIC), and r^2 are shown for each series (n=55).

SSEdis (pdq),(PDQ)	RMS[a]	AIC	r^2
$\tilde{Z}_t = (1 + .41\ B - .30\ B^3)\ a_t$ (3.5) (2.5)	207.	934.	17.7
NSEdis (pdq),(PDQ)	**RMS[a]**	**AIC**	**r^2**
$\tilde{Z}_t = (1 - .38\ B^2)\ a_t$ (2.9)	228.	938.	9.0

[a] $RMS/10^5$.

Table 5.17. Tentative ARMA models for inland (May-June) SST in southern, northern, and Southeast Alaska. T- statistics (below parameter estimates), residual mean square errors (RMS), Akaike Criteria (AIC), and r^2 are shown for each series (n=64 for SSEsst, and n=42 for NSEsst and SEsst).

SSEsst (pdq),(PDQ)	RMS	AIC	r^2
$(1+.28\,B^4)\tilde{Z}_t = (1+.26\,B^6)\,a_t$ (2.3) (2.1)	1.54	35.5	10.7
$(1+.23\,B^4-.27\,B^6+.22\,B^7)\tilde{Z}_t = a_t$ (1.9) (2.2) (1.8)	1.43	33.0	16.8

NSEsst (pdq),(PDQ)	RMS	AIC	r^2
$(1+.46\,B^8)\tilde{Z}_t = a_t$ (2.7)	1.35	18.5	12.2
$\tilde{Z}_t = (1-.81\,B^8)\,a_t$ (13.)	1.23	14.6	20.2
$\tilde{Z}_t = (1-.62\,B^8-.25\,B^{11})\,a_t$ (7.1) (2.7)	1.17	14.5	24.0

SEsst (pdq),(PDQ)	RMS	AIC	r^2
$(1+.40\,B^9)\tilde{Z}_t = a_t$ (2.4)	1.16	12.2	12.2
$\tilde{Z}_t = (1-.81\,B^9)\,a_t$ (14.)	1.03	7.24	21.7

accounts for 17% of the variability in the series and contains no diagnostic difficulties (note parameter slightly below 2 SE in significance). Other ARMA and MA models with terms for these 3 lags perform about as well as the model shown in Table 5.17.

The correlogram for northern Southeast Alaska SST (NSEsst) is similar to the correlograms of winter air temperatures. An SAR(8) model (Table 5.17, middle panel) fits the data adequately. An SMA(8) model has a lower RMS than the SAR model, but residual autocorrelations (lags 9 and 11) are high and the MA coefficient is not stable ($.41 \leq \Theta \leq .81$) across 5 estimations. The 2 parameter SMA model meets modeling specifications when estimation is performed with backcasting (BMDP), but a t-statistic for the lag 11 parameter is 1.6 when the model is estimated with the likelihood algorithm in the SCA program. Finally, since parameter estimates for the SMA(8) model varied greatly according to the estimation method, the SAR(8) model may be the better model.

Two models for the composite Southeast Alaska SST series (SEsst) are shown in Table 5.17. The SAR(9) model leaves nearly significant partial autocorrelations at lags 7 and 12, while the SMA(9) model leaves residual correlations which are significant at lag 7 and high at lags 12 and 1. No two parameter models for SEsst were found which satisfied all modeling specifications. Since the seasonal parameter in the SMA(9) model varies considerably with different estimation methods, it may be a poorer model.

5.5.5 Northeast Pacific Sea Surface Temperature

The strongest correlations in the Northeast Pacific SST series SST50w, SST55s, and SSTave (Figure C16) occurred near lags 1, 5, and 8. AR(1) models were fit to the SST50w and SSTave series (Table 5.18). However, residual autocorrelations at lags 5 and 10 (SST50w) or at lags 5 and 7 (SSTave) were nearly significant, and the AR(1) parameter became nonsignificant (±2 SE) during some of the 5 data-deleting estimations. A seasonal parameter for lag 5 added into the two AR(1) models (in different ways) to yield slightly better (4% to 9%) fit and increased stability (Table 5.18).

An AR(1) model was fit to the SST55s series (Table 5.18), but a significant autocorrelation remained in the residual series at lag 8. A multiplicative AR(1)-SAR(8) model for SST55s (Table 5.18, center panel) was the best model found for the series, but it also leaves a nearly significant correlation at lag 8 in the residual series. As might have been expected, an ARMA(1,0,8) $\theta_{1-7}=0$ model yielded better residual diagnostics and RMS, but the MA(8) parameter estimate varies significantly when estimations were performed with different algorithms.

Table 5.18. Tentative ARMA models for seasonal Northeast Pacific SST. T-statistics (below parameter estimates), residual mean square errors (RMS), Akaike Criteria (AIC), and r^2 are shown for each series. n = 35.

SST50w (pdq),(PDQ)	RMS	AIC	r^2
$(1-\underset{(2.6)}{.39}\,B)\tilde{Z}_t = a_t$	.153	-59.8	19.6
$(1-\underset{(2.7)}{.45}\,B)\,(1-\underset{(2.5)}{.43}\,B^5)\tilde{Z}_t = a_t$	.145	-59.6	23.7

SST55s (pdq),(PDQ)	RMS	AIC	r^2
$(1-\underset{(2.5)}{.37}\,B)\,(1+\underset{(2.9)}{.46}\,B^8)\tilde{Z}_t = a_t$	.303	-33.8	42.0

SSTave (pdq),(PDQ)	RMS	AIC	r^2
$(1-\underset{(2.4)}{.38}\,B)\tilde{Z}_t = a_t$	.134	-64.4	14.6
$(1-\underset{(3.1)}{.47}\,B)\tilde{Z}_t = (1+\underset{(10.)}{.79}\,B^5)\,a_t$	.121	-65.9	23.1

5.6 Discussion of Models for Environmental Parameters

Short series and weak cyclic (periodic interannual) autocorrelations present significant difficulties in modeling environmental time series. Relatively simple AR models exist for some series, but seasonal moving average parameters appeared in models for others. A low fraction of variability was explained by most models. When periodic seasonality is long and the time series are short, different conclusions could be reached when different algorithms were used to estimate model parameters.

Correlations for relatively long periods are important in these data. First order autocorrelation is generally low and hard to include in models with parameters for long period (seasonal) variations. Lower frequency (8-12 year) seasonal correlations are most important in the winter air temperature and inland SST series (except in Ketchikan) while higher frequency (5-8 year) correlations are most important in the Northeast Pacific SST series. Positive autocorrelations near lag 5 in the Northeast Pacific SST data suggest pseudo-cyclic behavior at about 5 years. Negative correlations at higher lags (8-12) in other series may be related to half-cycle (16 to 24 year) trends, but this could not be verified with these short series.

CHAPTER 6

FORECASTS FROM STOCK-RECRUIT MODELS AND CORRELATION BETWEEN AVERAGE WEIGHTS OF SALMON AND ENVIRONMENT DATA

Biologists generally consider life history information when building a model to predict the size of a salmon population. For example, recruitment of pink salmon which have a two-year life cycle, can be modeled as

$$R_t = \alpha S_{t-2} e^{-\beta S_{t-2}} \tag{6.1}$$

where R_t is recruitment (catch plus escapement) in year t, S_{t-2} is escapement in year t-2, and α and β are, respectively, parameters for density independent growth and density dependent mortality (Ricker 1954). The general form of this "Ricker" stock-recruit model is commonly used to forecast returns to Alaska salmon fisheries, and in Southeast Alaska an index of pink salmon escapement is available for analysis. Environmental and/or auxiliary information is frequently incorporated into this stock-recruit model. Because of the importance of this model, recruitment of pink salmon in Southeast Alaska fisheries was forecast to compare with results from time series analysis.

Average weight of salmon in commercial catches is a measure of overall growth for the harvested individuals. If the distributions of fish ages and contributions by fish stock to a fishery are relatively constant over time, and timing of the harvests does not vary greatly, average weight of individuals in the catch is probably a good index of overall growth for the returning population. These assumptions are not met in Southeast Alaska (e.g., Alexandersdottir 1987). Even so, correlations between average fish weight and environmental data are contrasted with life history features to suggest if overall growth could still be related to catch and recruitment.

6.1 Forecasts from Stock-Recruit Models

Recruitment (R_t) in the Ricker model is obtained by adding observed catches C_t to estimated escapement S_{t-x}. Since escapement data for pink salmon in Southeast Alaska is an index S^* of peak escapement (Chapter 2), an estimate of d in the relation

$$S_{t-2} = d\, S^*_{t-2} \tag{6.2}$$

is needed to estimate R_t and correctly apply the model. In addition, fitting data to (6.1) requires the placement of a stochastic term for random variation. Several authors (Peterman 1981; Walters 1986) have argued for a multiplicative, log-normal distribution of random noise in stock-recruitment models, and this recommendation was followed in this analysis. Ordinary least squares was used to estimate (6.1) in the form

$$\ln(R_t) = \alpha^* + \ln(S_{t-2}) - \beta S_{t-2} + \varepsilon_t \tag{6.3}$$

where $\alpha^* = \ln(\alpha)$ and ε_t is normally distributed with mean 0 and variance σ^2. Note that (6.3) can also be rearranged so that $\ln(R_t/S_{t-2})$, an index of survival, is on the left hand side of the equation. Diagnostic checks of the regression models included checking for autocorrelated residuals (±2 SE), and deleting data to check for stability of the parameter estimates (as in Section 5.1). Standard errors for the log-transformed forecasts were estimated in PROC REG (SAS Institute Inc. 1988). Since the multiplicative-error form of the Ricker model was adopted, forecasts of recruitment were corrected for bias using the relation (Noakes et al. 1990)

$$R_t = e^{R_t' + 0.5\sigma^2} \tag{6.3}$$

where R_t' is the forecast of $\ln(R_t)$ from (6.3) and σ^2 is residual variance.

Escapement indices for fishing districts in southern and northern Southeast Alaska (Section 2.1) were obtained from ADF&G (Karl Hofmeister, Douglas, AK., personal communication, 1992). An index for southern Southeast Alaska was made by summing the indices for districts 101-103 and 105-108, as recommended by ADF&G. An index for northern Southeast Alaska was made by adding the indices for districts 109-114 (district 115 was excluded because four years of data are missing). An escapement index for Southeast Alaska was constructed by adding the indices for northern and southern Southeast Alaska. Recruitment to each area was estimated by adding catches (Tables A1-A3) to estimates of escapement derived from the indices according to equation 6.2.

Assuming that density dependent mortality can be observed in data for Southeast Alaska, the value of d in (6.2) will influence estimates of α and β in (6.3). An empirical study to identify a value for d was thus conducted by fitting (6.3) to odd-, even-, and combined-year pink salmon data for southern, northern, and southeast Alaska with d set to 1, 1.5, 2, ..., 4. In each of the 63 regressions the t-statistic for β was less than $|1|$. Density dependent mortality was obviously not visible in the data, so d=2.5 was used in subsequent analysis. The value of d=2.5 is used by ADF&G in Southeast Alaska to convert peak counts (of pink salmon) to an estimate of escapement.

Environmental variables were incorporated into the stock-recruit (SR) model by assuming the exogenous variables influence mortality in a linear fashion. The Ricker model with two environmental variables is

$$\ln(R_t) = \alpha^* + \ln(S_{t-2}) - \beta S_{t-2} + \gamma T_{t-i} + \xi U_{t-j} + \varepsilon_t \tag{6.4}$$

where T and U are the (exogenous) environmental variables, γ and ξ are parameters to be estimated, and i and j are times for delay between environmental effect and recruitment to the fishery.

To identify correlates, cross-correlations $\{r_{xy}(k)\}$ between $\ln(R_t/S_{t-2})$ and environmental data (Chapter 3) were computed for combined data (Table 6.1), or Pearson correlations (r_{xy}) were computed between $\ln(R_t/S_{t-2})$ and lagged even-year (Table 6.2) or odd-year (Table 6.3) environment data, from lag 0 to lag 3. Standard errors of $r_{xy}(k)$ are estimated as $1/(n-k)^{0.5}$, which assumes one series is white noise (Box and Jenkins 1976). Standard errors of Pearson correlations are from Rohlf and Sokal (1981).

Twenty of the 288 correlations (7%) between $\ln(R_t/S_{t-2})$ and environmental data were significant at the 95% level, 13 at lags expected to be important (see Table 3.2 for a summary of hypothesized lag relations). Eight of these 13 correlations involved winter air temperatures at lag 1, suggesting effects on incubating eggs are important. Other significant correlations at lags expected to be important involve upwelling (SEupw) at lag 1 (Table 6.1), and wind speed (Nwind) at lag 1, November-June SST (SSTave) at lag 0, and summer sea surface temperature at 55^o N (SST55s) at lag 1 (Table 6.3).

Four of the 7 significant correlations which occurred at lags not expected to be important involved inland SST at lag 2, suggesting survival of progeny is related to SST experienced by parents. The significant correlations between $\ln(R_t/S_{t-2})$ and November-June SST (SSTave) at lag 1 (Table 6.1), low winter air temperature (SEcold) at lag 2 (Table 6.2), and fall discharge (SSEdis) at lag 3 (Table 6.3), are probably spurious. Given an error rate (α) of 0.05, one would expect 5% of 288, or ≈14 significant correlations due to chance alone.

The exogenous variable most strongly correlated to $\ln(R_t/S_{t-2})$ for combined even- and odd-year data in each fishing area (SSEsst in southern, NSEwint in northern, and SEwint in Southeast Alaska) were incorporated into the SR models (6.4) for each

Table 6.1. Cross-correlations between $\ln(R_t/S_{t-2})$ of **combined even- and odd-year pink salmon** in southern, northern, and Southeast Alaska, and environmental data 0 to 3 years before the catch, 1962-1985.

	Lag in Years Before Catch[a]			
SSE vs.	0	1	2	3
SSEdis	**-.246**	-.088	.020	.229
SSEcold	.061	**.376**	.106	.018
SSEwint	.234	**.418u**	.138	-.056
SSEsst	.010	.162	**.491u**	-.008
SEupw	.030	**-.407**	-.004	.020
Nwind	.175	-.071	**-.413**	-.117
SST55s	.007	.255	.155	**.293**
SSTave	.251	**.310**	.024	.197
NSE vs.	0	1	2	3
NSEdis	**-.371**	.134	.366	-.192
NSEcold	.151	**.435u**	.205	-.215
NSEwint	.209	**.436u**	.363	-.133
NSEsst	.215	**.352**	.196	-.009
SEupw	**.172**	-.027	.016	-.008
Nwind	.211	-.245	-.175	**-.263**
SST55s	.148	**.398**	.151	.307
SSTave	.257	**.367**	.198	.164
SE vs.	0	1	2	3
SEdis	**-.321**	-.113	.218	.016
SEcold	.167	**.479u**	.186	-.040
SEwint	.300	**.508u**	.266	-.111
SEsst	.201	.214	**.437u**	.113
SEupw	.102	-.298	.025	.008
Nwind	.178	-.166	**-.356**	-.187
SST55s	.105	**.381**	.194	.338
SSTave	.310	**.424u**	.106	.218

[a] Lags expected to be important are underlined and the highest correlation between variables is bold. Significant correlations ($P \leq 0.05$) are indicated with a **u**.

Table 6.2. Correlations between $\ln(R_t/S_{t-2})$ of **even-year pink salmon** in southern, northern, and Southeast Alaska, and environmental data 0 to 3 years before the catch, 1962-1984.

	Lag in Years Before Catch[a]			
SSE vs.	0	1	2	3
SSEdis	-.241	**.281**	.112	-.159
SSEcold	**.508**	.493	.378	.189
SSEwint	.105	**.546**	.377	.319
SSEsst	.220	.047	**.305**	.040
SEupw	.123	-.312	-.046	**-.325**
Nwind	-.015	**.621u**	.110	-.022
SST55s	.326	**.447**	.018	.296
SSTave	**.628u**	.323	.181	.345
NSE vs.	0	1	2	3
NSEdis	**-.401**	.121	.392	-.134
NSEcold	**-.448**	.351	.283	-.179
NSEwint	-.060	**.485**	.356	.016
NSEsst	.394	**.500**	.234	-.029
SEupw	.327	**.500**	.008	-.332
Nwind	**.324**	-.125	-.229	.018
SST55s	-.119	**.562**	-.043	.411
SSTave	.232	.266	**.442**	.257
SE vs.	0	1	2	3
SEdis	**-.491**	.358	.015	-.200
SEcold	.154	.543	**.604u**	.117
SEwint	.024	**.720u**	.535	.230
SEsst	**.497**	.326	.449	.223
SEupw	.243	.046	-.019	**-.455**
Nwind	.155	**.358**	-.070	.006
SST55s	.137	**.632u**	.056	.444
SSTave	**.574**	.379	.381	.413

[a] Lags expected to be important are underlined and the highest correlation between variables is bold. Significant correlations (P≤0.05) are indicated with a **u**.

Table 6.3. Correlations between $\ln(R_t/S_{t-2})$ of **odd-year pink salmon** in southern, northern, and Southeast Alaska, and environmental data 0 to 3 years before the catch, 1963-1985.

	Lag in Years Before Catch[a]			
SSE vs.	0	1	2	3
SSEdis	-.391	-.157	.057	**.669u**
SSEcold	-.073	**.491**	.244	-.007
SSEwint	.304	**.530**	.177	-.282
SSEsst	-.007	.276	**.792u**	-.106
SEupw	-.038	**-.625u**	-.195	.097
Nwind	.314	-.302	**-.473**	-.168
SST55s	-.075	.219	.332	**.559**
SSTave	.142	**.280**	.071	.269
NSE vs.	0	1	2	3
NSEdis	-.364	.157	**.440**	-.201
NSEcold	.398	**.712u**	.328	.338
NSEwint	.388	.355	**.473**	-.025
NSEsst	.096	.209	.263	**.324**
SEupw	-.004	**-.506**	-.214	-.014
Nwind	.113	**-.398**	.124	-.269
SST55s	.312	.172	.338	**.436**
SSTave	.281	**.524**	-.045	.159
SE vs.	0	1	2	3
SEdis	-.338	-.352	.471	**.567**
SEcold	.219	**.728u**	.301	.119
SEwint	.431	**.502**	.316	-.244
SEsst	.102	.209	**.687u**	.202
SEupw	-.002	**-.639u**	-.246	.072
Nwind	.227	**-.380**	-.230	-.200
SST55s	.114	.270	.391	**.574**
SSTave	.222	**.457**	.039	.267

[a] Lags expected to be important are underlined and the highest correlation between variables is bold. Significant correlations ($P \leq 0.05$) are indicated with a **u**.

area. Multivariate models were not fit to the short (n=12) series of recruitment for odd- or even-year pink salmon lines.

Residuals from each SR model were again cross-correlated with environmental data to search for more correlates. No additional correlates (±2 SE) were found for the northern Southeast model. In contrast, residuals from the model for southern Southeast Alaska were significantly correlated (±2 SE) with low winter air temperatures (SSEcold) at lag 1, and residuals from the model for Southeast Alaska are significantly correlated with SEsst at lag 2. These variables were thus included in the models (Table 6.4). Stock size, winter air temperature, and inland SST could thus account for 50% to 56% of the variability in $\ln(R_t/S_{t-2})$ in southern and Southeast Alaska, respectively. Parameters for density dependent mortality (β in 6.4) were not significant in any estimations and were dropped from the models. Residuals from the final models were not significantly correlated with other series, nor were they autocorrelated. However, t-statistics for the parameter α^* in the model for northern Southeast Alaska were low (t=1.3), showing that stock size is a weak predictor of return, or that escapement in the northern area is indexed with relatively high error.

Average forecast error (bias, MPE) from the stock-recruit models (Table 6.5) was near 0, unlike the forecasts of pink salmon catch or recruitment (Tables 5.3 and 5.13) which tended to underestimate returns by 20% or more between 1981 and 1985. Average absolute forecast error (MAPE) for southern Southeast Alaska (26%) was within 2 percentage points of MAPE from the univariate model of recruitment (Table 5.13) and within 3 percentage points of MAPE from the univariate model of catch (Table 5.3). The MAPE for northern Southeast Alaska SR model (40%) was 7-9 percentage points *higher* than MAPE from the univariate models of recruitment or the AR(2) $\phi_1=0$ model for the short-term series of catch (Table 5.13), but 10 percentage points lower than MAPE from the univariate model for the long-term series of catch (51%, Table 5.3). In contrast, MAPE from the SR model for Southeast Alaska (14%) was 9 percentage points below MAPE from the univariate model of recruitment (Table 5.13) and 16-19 percentage points below MAPE from the univariate models of catch (Tables 5.3 and 5.13). Thus, while forecasts of pink salmon catch can be derived from forecasts of recruitment from SR models (Chapter 11), forecasts of catch derived from forecasts of recruitment from SR models are unlikely to be more precise (1981-1985) than forecasts from univariate models except possibly for Southeast Alaska in its entirety.

Table 6.4. Parameter estimates for stock-recruit models of pink salmon returns to southern, northern, and Southeast Alaska, 1962-1985. The parameter γ is for the air temperature variable ($SSEcold_{t-1}$ in southern, $NSEwint_{t-1}$ in northern, and $SEwint_{t-1}$ in Southeast Alaska), ξ is a parameter for sea surface temperatures ($SSEsst_{t-2}$ in southern and $SEsst_{t-2}$ in Southeast Alaska), and α^* is a parameter for density independent effects.

Southern Southeast Alaska. n = 24, r^2= 0.73

Parameter	Estimate	Std. Error	t	P > | t |
α^*	-9.226	2.577	-3.58	0.002
ξ	0.178	0.050	3.55	0.002
γ	0.040	0.012	3.30	0.003

Northern Southeast Alaska. n = 24, r^2= 0.35

Parameter	Estimate	Std. Error	t	P > | t |
α^*	-0.863	0.642	-1.35	0.192
γ	0.047	0.022	2.16	0.042

Southeast Alaska. n = 24, r^2= 0.73

Parameter	Estimate	Std. Error	t	P > | t |
α^*	-8.705	2.326	-3.74	0.001
ξ	0.157	0.047	3.34	0.003
γ	0.048	0.014	3.42	0.002

Table 6.5. Forecast and estimated recruitments (Returns), and relative errors of forecasts from stock-recruit models of **pink salmon recruitment** in southern (SSE), northern (NSE) and Southeast (SE) Alaska fishing areas. Recruitment in numbers/10^7.

	Southern Southeast Forecast Return			Estimated	Forecast Error	
yr	Lo 80%	Point	Up 80%	Return	PE	APE
81	1.607	2.617	3.857	2.825	-7.4	7.4
82	2.358	3.719	5.544	2.793	35.7	35.7
83	1.857	3.034	4.516	5.197	-41.6	41.6
84	2.061	3.401	5.061	4.338	-21.6	21.6
85	4.448	7.500	11.419	6.163	21.7	21.7
86	3.538	5.717	8.377			
				median	-7.4	21.7
				mean	-2.6	25.6

	Northern Southeast Forecast Return			Estimated	Forecast Error	
yr	Lo 80%	Point	Up 80%	Return	PE	APE
81	1.101	2.294	3.873	1.498	53.1	53.1
82	0.649	1.356	2.310	2.100	-35.4	35.4
83	0.696	1.447	2.443	1.660	-12.8	12.8
84	1.081	2.235	3.784	1.467	52.4	52.4
85	1.035	2.078	3.436	3.989	-47.9	47.9
86	1.016	2.107	3.543			
				median	-12.8	47.9
				mean	1.9	40.3

	Southeast Alaska Forecast Return			Estimated	Forecast Error	
yr	Lo 80%	Point	Up 80%	Return	PE	APE
81	3.122	4.811	6.835	4.337	10.9	10.9
82	3.696	5.708	8.167	4.895	16.6	16.6
83	3.297	5.228	7.706	6.860	-23.8	23.8
84	3.720	5.665	8.022	5.807	-2.4	2.4
85	5.741	8.676	12.236	10.154	-14.5	14.5
86	5.710	8.463	11.726			
				median	-2.4	14.5
				mean	-2.6	13.7

It may also be significant that relative forecast errors from the SR models for southern and northern Southeast Alaska are somewhat opposite, and tend to cancel each other (Table 6.5). This tendency was also observed for models of catch (Section 5.4).

6.2 Correlation Between Average Weight and Environment Data

Estimation of average weights for salmon landed in Southeast Alaska is described in Section 2.3. Cross-correlations between salmon average weight (AWT) and environmental data (Table 3.1) were calculated to lag 3 for pink salmon, and to lag 5 for other species. Thus, correlations to one year beyond the assumed principal age at maturity were calculated for each species except sockeye salmon, which were characterized as maturing at 5 years of age (Chapter 2). Autocorrelations of the AWT series were calculated (Table 6.6) to permit modeling of the series.

Three significant correlations between pink salmon AWT and environmental data were significant (Table 6.7). Two of these correlations involve SEsst at lag 2 (r=-0.34 and r=-0.61), and one involves SST55s at lag 0 (r=0.34). The correlations with SEsst are coincident with the significant correlations found between $\ln(R_t/S_{t-2})$ and SEsst at lag 2 (Tables 6.1 and 6.3). The correlation with SST55s at lag 0 is probably spurious since pink salmon bound for Southeast Alaska enter inland waters by July or August, and since correlations with SEsst at lag 0 are weak. The pink salmon series was weakly correlated at low lags, tentatively suggesting an AR(2), an MA(4), or perhaps a ARMA model for the series (Table 6.6).

Significant correlations between chum salmon AWT and SEsst were found at lags 2 and 3, and a significant correlation with Nwind occurred at lag 1 (Table 6.8). The correlations with SEsst at lag 2 and 3 involve chum salmon that mature at 3 and 4 years of age during their first months at sea (Table 3.2). In contrast, the correlation with Nwind does not involve juvenile migrations of chum salmon that mature at 3, 4, or 5 years of age, and is more likely to be spurious. Chum salmon AWT is correlated at low lags (Table 6.6), suggesting the model for pink salmon applies to this data as well.

The sockeye salmon AWT data was strongly autocorrelated, and can be considered nonstationary; the correlogram for first differences in AWT (Table 6.6) suggests the appropriate model for this series is ARIMA(0,1,1). I did not correlate residuals from this model with environmental data, but note that the original series is significantly correlated with SST55s through lag 3 (Table 6.8). The correlations at lags 1 to 3 are reasonable because sockeye are at sea during this period, but the value at lag

Table 6.6. Autocorrelation (ACF) and partial autocorrelation (PACF) functions for **pink, chum, sockeye,** and **coho** salmon **average weights** in Southeast Alaska. The correlations for sockeye salmon are for series after taking differences at lag 1 (∇AWT).

	Lag in Years[a]					
Pink	1	2	3	4	5	6
ACF	.280u	.297u	.248	.290u	.091	.202
PACF	.280u	.237	.135	.170	-.092	.091
Chum[b]	1	2	3	4	5	6
ACF	.498u	.449u	.294u	.350u	.213	.351
PACF	.498u	.267u	-.003	.177	-.056	.223
Sockeye	1	2	3	4	5	6
ACF	.245u	.140	.075	.180	.159	-.012
PACF	.245u	.085	.024	.157	.086	-.106
Coho	1	2	3	4	5	6
ACF	-.432u	-.079	-.004	-.030	.133	.048
PACF	-.432u	-.327u	-.264u	-.274u	-.073	.112

[a] Significant correlations ($P<0.05$) are indicated with a **u**.

[b] Estimated AWT of chum salmon in 1924 (12.45 lb, Marshall and Quinn 1988) considered an outlier and changed to series mean (8.95 lb).

Table 6.7. Cross-correlations between average weights of combined even- and odd-year pink salmon (Even+Odd) and correlations between average weights of even- or odd year pink salmon in Southeast Alaska, and environmental data lagged 0 to 3 years before the catch.

			Lag in Years Before Catch[a]			
	Variable	n	0	1	2	3
Even+Odd	SEdis	55	**.190**	.059	-.054	.112
	SEcold	36	.169	-.112	**-.250**	.042
	SEwint	71	.199	-.141	**-.233**	-.003
	SEsst	42	.089	-.205	**-.339u**	-.202
	SEupw	40	.086	.011	-.014	**.166**
	Nwind	40	**-.233**	-.111	.020	-.011
	SST55s	35	**.339u**	.197	.096	.031
	SSTave	35	**.122**	.019	-.106	.031
	Variable	n	0	1	2	3
Even	SEdis	26	.156	**-.225**	.082	.208
	SEcold	16	**.376**	-.307	-.139	.290
	SEwint	35	.142	**-.329**	-.260	.141
	SEsst	20	.079	-.228	-.135	**-.399**
	SEupw	18	.224	-.132	-.153	**.258**
	Nwind	18	**-.324**	-.033	.159	.264
	SST55s	16	**.340**	.277	.111	-.125
	SSTave	16	**.415**	.159	-.215	.005
	Variable	n	0	1	2	3
Odd	SEdis	26	.261	**.298**	-.097	-.033
	SEcold	17	.079	.238	**-.356**	-.145
	SEwint	36	**.251**	.013	-.245	-.126
	SEsst	20	.208	-.177	**-.609u**	-.039
	SEupw	19	-.098	.087	**.136**	.093
	Nwind	19	-.080	-.122	-.024	**-.291**
	SST55s	16	.325	.102	-.033	**.340**
	SSTave	16	**-.151**	.044	.116	.068

[a] Lags expected to be important are underlined and the highest correlation between variables is bold. Significant correlations (P≤0.05) are indicated with a **u**.

Table 6.8. Cross-correlations between average weight of chum, sockeye, and coho salmon in Southeast Alaska and environmental data, 0 to 5 years before the catch.

		Lag in Years Before Catch[a]					
Chum vs.[b]	n	0	1	2	3	4	5
SEdis	55	**-.216**	-.152	-.051	-.120	<u>-.091</u>	-.090
SEcold	36	**.223**	.139	-.190	<u>-.071</u>	-.027	-.028
SEwint	74	.093	-.023	-.212	**-.220**	-.103	-.192
SEsst	42	.022	-.052	-.355u	<u>**-.403u**</u>	-.084	-.071
SEupw	40	-.028	.212	**.289**	<u>-.019</u>	-.250	-.144
Nwind	40	-.236	**-.364u**	-.081	<u>.112</u>	.087	-.084
SST55s	35	**.252**	<u>.234</u>	<u>-.034</u>	<u>-.198</u>	-.219	-.009
SST50w	35	<u>-.038</u>	<u>.100</u>	<u>.161</u>	-.127	**-.228**	-.057
Sock vs.	**n**	**0**	**1**	**2**	**3**	**4**	**5**
SEdis	55	-.226	-.119	-.120	-.227	**-.250**	<u>-.204</u>
SEcold	36	.039	.126	**-.175**	-.023	<u>.051</u>	.126
SEwint	75	.023	-.035	**-.173**	-.054	<u>-.090</u>	-.019
SEsst	42	-.093	-.121	**-.214**	<u>-.119</u>	.020	.029
SEupw	40	.019	.039	**.122**	<u>.084</u>	.008	-.029
Nwind	40	-.114	-.117	-.105	<u>**-.160**</u>	-.130	.077
SST55s	35	-.368u	<u>-.355u</u>	<u>**-.495u**</u>	<u>-.357u</u>	-.244	-.141
SST50w	35	<u>.005</u>	<u>-.004</u>	<u>**-.216**</u>	.077	.094	-.067
Coho vs.	**n**	**0**	**1**	**2**	**3**	**4**	**5**
SEcdis	55	.026	.141	.173	.081	<u>.047</u>	**.317u**
SEcold	36	.092	-.065	**-.154**	<u>.049</u>	.123	.094
SEwint	68	**.382u**	.166	.059	<u>.287u</u>	.043	.109
Lowsdis	55	-.133	-.023	<u>.125</u>	<u>-.038</u>	.006	**.156**
SEsst	42	.136	<u>-.094</u>	**-.169**	.116	.100	-.009
SEupw	40	-.074	<u>-.003</u>	-.071	.100	**-.212**	.049
Nwind	40	.086	<u>.059</u>	**.270**	-.086	.041	.146
SST55s	35	**.285**	<u>-.019</u>	.070	.247	.267	.223
SSTave	35	<u>.158</u>	.084	-.176	.110	**.226**	.201

[a] Lags expected to be important are underlined and the highest correlation between variables is bold. Significant correlations (p≤0.05) are indicated with a **u**.

[b] Estimated average weight of chum salmon in 1924 (12.45 lb, Marshall and Quinn 1988) considered an outlier and changed to series mean (8.95 lb).

0 is not since the fish enter inland seas by July or August, and the correlation with SEsst at lag 0 is small (r=-0.09). The high correlation at lag 0 may result because both series are highly autocorrelated. It is interesting that the correlations with SST are negative, indicating high SST is associated with low average weight. Ricker (1981) and other authors report similar correlations for sockeye salmon bound for British Columbia.

Three significant correlations between the environmental data and coho salmon average weight were observed (Table 6.8). Only one of these, a low (r=0.29) correlation with winter air temperature, occurred at lag expected to be important from life history data. The significant correlation between coho salmon AWT and SEcdis at lag 5 is interesting, but would be easier to relate to life history information if the correlation at lag 4 (which involves the dominant age at maturity) was not so small. The correlogram for coho salmon AWT suggests the MA(1) model for these data.

6.3 Discussion

The correlations found in this analyses do not support many of the varied hypotheses (Chapter 3) relating pink salmon mortality and environmental variations in Southeast Alaska. Mean or low winter air temperature data is significantly correlated with an index of pink salmon survival (at lag 1) in 6 of the 9 area×brood-year series compiled for Southeast Alaska, but individually only 8 of the 18 correlations with air temperature were significant. Average weights of sockeye salmon were inversely related to summer SST in the Northeast Pacific at 55^{o}N, as noted by Ricker (1981) and others.

Significant correlations also occur between inland SST and the survival index for odd-year pink salmon in southern and Southeast Alaska, suggesting SST experienced by odd-year pink salmon could influence growth and/or survival of their progeny. Similar results are reported by Willette (1985), who studied survival of pink salmon in Prince William Sound. Since the correlation between inland SST and the index of survival for northern Southeast Alaska is not significant, the overall significance of the correlations for Southeast Alaska is unclear.

Density dependent mortality was not apparent in the data for Southeast Alaska (1962-1985), although some density dependence may escape detection because of errors in indexing escapement (Walters 1986). The lack of a strong (nonlinear) density dependent effect in these data may help explain why the univariate models of catch and recruitment (Chapter 5) perform as well as they do. However, strong density dependent responses must occur at some level of abundance, and future stock-recruitment models for Southeast Alaska may have to include this factor to avoid large forecast errors.

Forecasts from the SR models were notably less biased than forecasts from the univariate models of catch or recruitment, and about equally precise (Figure 6.1). Within fishing areas, forecast errors from SR models of return, and forecasts from time series models of return (or catch, Figure 5.1) exhibit similar deviations from actual values, illustrating how the large departures from forecast values dominate the data.

In contrast, forecasts from the SR model for Southeast Alaska were more precise than forecasts from the individual areas. Also, forecast errors from models for southern and northern Southeast Alaska tend to oppose each other. These results could occur for several reasons. First, they could occur due to chance. Second, unexpected large or small returns in one area (e.g., southern Southeast Alaska) could strongly influence (reduce or increase) effort and catch in the other area (northern Southeast Alaska) in an opposite, compensating, reaction. Such a reaction could be related to economic factors. Third, summarizing recruitment and/or the predictor variables (escapement and temperature) over the larger geographic area (Southeast Alaska) could significantly reduce opposing biases in data compiled for the individual areas. For example, escapements in one area in year t could contribute substantially to catch landed in another area in year t+2. This could occur if substantial numbers of fish are caught as they migrate between areas to spawn. Finally, the opposing deviations could actually result from opposing ecological and/or environmental influences. If this was true, then at least some of the spatial and temporal relationships assumed common to the two runs of pink salmon (e.g., high seas distributions) would have to be false.

Average weights of pink salmon landed in the fishing districts of Southeast Alaska (ADF&G computer summary dated 11/08/90) exhibit some similarity to the forecast errors between 1981 and 1985, especially in northern Southeast Alaska (Figure 6.1). Indices of growth for juvenile salmon might thus improve forecasts of the catches.

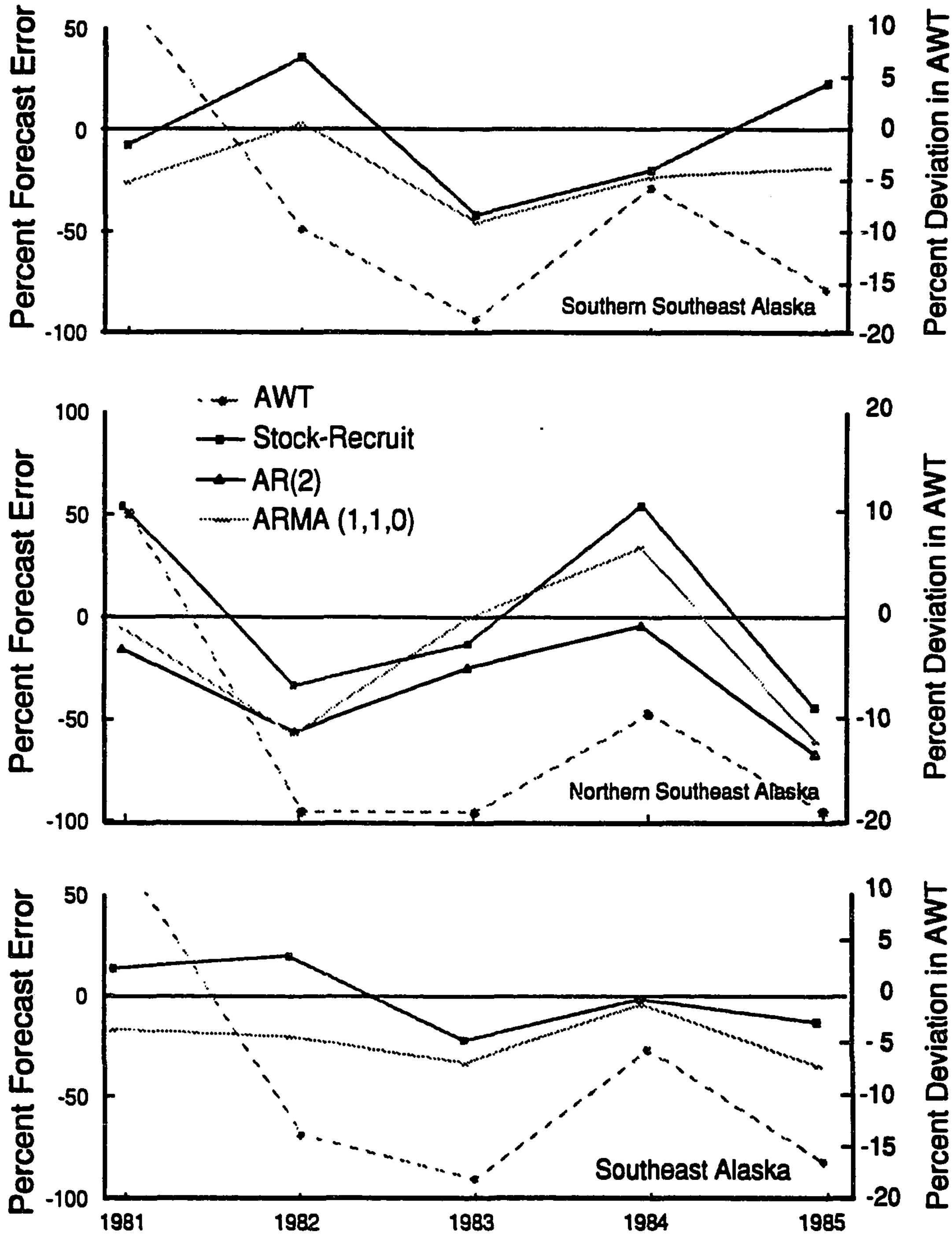


Figure 6.1. Deviations in average weight, and percent forecast error for stock-recruit and ARMA models of pink salmon return in southern, northern, and Southeast Alaska.

CHAPTER 7
MULTIVARIATE TIMES SERIES THEORY: ONE DEPENDENT VARIABLE

Let X_t and Y_t denote deviations from equilibrium levels of input and output in a system where observations are collected at equi-spaced times t=1,2,...,n. Assume an effect of X on Y may persist across time and that Y does not influence X. Box and Jenkins (1976) show that many systems with these characteristics can be modeled with

$$Y_t = \sum_{i=0}^{\infty} v_i X_{t-i} + N_t = v(B) X_t + N_t \tag{7.1}$$

where $v(B) = (v_0 + v_1 B + v_2 B^2 + ...)$ is called a transfer function and $\{v_i\}$ i=0,1,2,.. are (impulse response) weights, some of which may be zero, and N_t is a noise process independent of the X series. In particular, these authors show that parsimonious models for a system with one input and one output can be constructed by identifying the orders r and s of a rational form of $v(B) = \delta(B)^{-1} \omega(B) B^b$ where

$$\omega(B) = (\omega_0 - \omega_1 B - \omega_2 B^2 - ... - \omega_s B^s)$$

$$\delta(B) = (1 - \delta_1 B - \delta_2 B^2 - ... - \delta_r B^r)$$

and b is a time delay in the response of Y_t to X_t.

Allowing N_t to be an ARMA process, Box and Jenkins defined a transfer function-noise (TFN) model for m stationary series:

$$Y_t = \sum_{i=1}^{m} \delta_i(B)^{-1} \omega_i(B) X_{i,t-b} + N_t, \qquad N_t = \phi(B)^{-1} \theta(B) a_t \tag{7.2}$$

Regular and seasonal differencing operations can be applied to each series, including N_t, if required. Notation for differencing and seasonal models is described in Chapter 4.

7.1 Model Identification

Tentative identifications for a TFN model are made from plots of cross-correlations or impulse response weights. In the case of 2 stationary series which are not autocorrelated, X is identified as a leading indicator of Y if statistically significant cross-correlations occur when X leads Y in time and no significant cross-correlations occur when Y leads X in time. However, sample cross-correlations are difficult to use for model building if X and Y are nonstationary or highly autocorrelated.

Because models relating correlated time series may be hard to identify correctly, identification procedures tend to depend on the time series being considered. Vandaele (1983, Chapter 11) provides a good introduction to basic identification practices. In the case of one input and one output, Box and Jenkins (1976) suggest that identification of the orders (r,s,b) and the form of $v(B)$ begins by estimating $v(B) = \hat{r}_{\alpha\beta}(k)\,[s_\beta/s_\alpha]$, $k \geq 0$ from cross-correlations $\hat{r}_{\alpha\beta}(k)$ and standard deviations s of the filtered series

$$\alpha_t = \theta_x(B)^{-1}\phi_x(B)\,x_t$$

$$\beta_t = \theta_x(B)^{-1}\phi_x(B)\,y_t \qquad (7.3)$$

where x_t and y_t denote transformed (to stationary) series X_t and Y_t. Filtering (prewhitening) X_t and Y_t by the univariate model for x_t removes covariance between $\{\hat{r}_{xy}(k)\}$, which arises when both series are autocorrelated.

After filtering the series (or when the input is white noise) the estimated variance of the correlation var$[\hat{r}_{\alpha\beta}(k)]$ is approximately $(n-k)^{-1}$ (Box and Jenkins 1976). A tentative identification of model orders r, s and b is then made by comparing the significant $\{\hat{r}_{\alpha\beta}(k)\}$ or $\{\hat{v}_i\}$ to cross-correlations or impulse response weights from known processes. If the pattern from the sample is cut-off like the PACF for an autoregressive process, then $\delta(B)=1$ and $\omega(B)$ are tentatively identified as the significant terms of $\{\hat{v}_i\}$; otherwise formulae are used to determine r,s and b. These formulae are found in most books which describe transfer function-noise models.

Correct model identifications are even more difficult when multiple and correlated inputs are considered. If correlations are not large, Vandaele (1983) suggests the single-input procedure be applied to each variable independently. Then, Vandaele suggests, the series

$$\varepsilon_t = y_t - \sum_{i=1}^{m} \hat{v}_i(B)\,x_{it} \qquad (7.4)$$

is used, as usual, to identify a model for N_t prior to final estimations and diagnostic checking. This approach is justified because only model orders are initially being estimated.

Liu and Hanssens (1982) propose a more general procedure for models having m correlated inputs: jointly estimating the impulse response weights for all m series using ordinary least squares. Pre-filtering each series by the autoregressive factors that are common to all series is employed to maintain numerical accuracy. If the residuals are not white noise the weights can be estimated together with a noise model using nonlinear least squares. An extension of the corner method (Bequin, Gourieroux, and Monfort 1980) is then useful for expressing $\{v_i\}$ in rational form (Liu and Hanssens 1982).

Other identification procedures are also used. For example, Y and X can be prewhitened by their own univariate models before computing cross-correlations (Priestley 1971; Haugh and Box 1977; Pierce 1977), or residuals from the univariate model for Y could be cross-correlated with stationary X (see Vandaele 1983, p.291 for further dialogue on prewhitening Y).

7.2 Notation

Many analysts let X_t and Y_t denote actual observations instead of deviations from series means when modeling a time series. In this case, a constant (C) is added to the right-hand side of the general univariate or multivariate equation [e.g., (7.1)]. Then, for example, $C/(1-\phi_1-\phi_2-...-\phi_p)$ is the estimated mean of Z_t for a univariate AR(p) model. In the TFN model, C is a function of the estimated means of Y and X. When this procedure is employed during multivariate modeling, the effects (on forecasts, for example) of removing the constant from the model because the standard error of C is relatively high are not obvious. Thus, a judicious choice of rules for removing C from a model should be employed if this methodology is adopted.

7.3 Model Building and Diagnostic Checking

TFN models are usually constructed in an iterative cycle of identification, estimation, and diagnostic checking similar to that used for univariate models (Section 4.5). Various Portmanteau statistics (Box and Jenkins 1976; Pierce 1977) may be used to test for correlation of residuals or for unidirectional "causality" (Granger and Newbold 1986).

Residuals from a TFN should be uncorrelated with each input series. To check for this independence, the residuals $\{a_t\}$ should be cross-correlated with the input series (if it is white noise) or the filtered input series. If the residuals are autocorrelated but uncorrelated with the inputs, the noise model is suspected to be inadequate. If the residuals are autocorrelated and correlated with the (prewhitened) input(s), then the transfer function model is inadequate.

7.4 Modeling Alaska Catch and Environment Data

Because even- and odd-year pink catches skip years, and annual environmental data does not, traditional TFN modeling procedures cannot be employed for these series. However, even- and odd-year pink salmon catches can be combined for modeling purposes. This doubles the sample size, and by analogy to the results in 5.2.1.3, should not negatively impact results.

Modeling catch and environmental data is problematic when environmental series vary greatly in length, with some series being much shorter than the series of catch. This occurs in the data for Southeast Alaska, and two solutions to the problem are obvious. First, all series can be truncated to the same length. If this method is used, the series can be truncated to begin when the SST series begin (1951, Section 3.6). The advantage of using this approach is that statistics generated for model fit and parameter significance retain their usual interpretation.

A second approach, however, is to append series mean values to the beginning of relatively short exogenous series to make their length equal to the catch series. This method maximizes the use of available environmental information and the probability that catches can be modeled as stationary series. When this method is used, the part of residual variance which results from fitting $\{Y_i\}$ with mean values of X is relatively greater than the part where variation in Y_i tends to be "explained" by X_i. Statistics used for gauging significance of parameter estimates (and statistics like r^2) will thus appear less significant than they would, if for example, an appropriately truncated Y series, and the original X series, are modeled together.

If the series for Southeast Alaska are truncated to begin in 1951, about half the catch and up to half of the available environmental data are lost, the multivariate identification and estimation procedures lose stability, and the estimated means of the series are greatly lowered. Thus, forecasts made from any stationary model will be biased. The significance of this bias is illustrated by the fact that mean values estimated for all but one catch series (coho salmon in northern Southeast Alaska) truncated to begin in 1951 are below lower 95% confidence intervals (using normal theory) for mean values estimated from the untruncated series. Thus, if these series are truncated at 1951, they probably should be modeled as nonstationary series.

CHAPTER 8
MULTIVARIATE TIME SERIES MODELS: ONE DEPENDENT VARIABLE

Transfer function-noise (TFN) models relating salmon catch and environmental data are developed in this chapter. Catch in numbers of salmon landed are used in each analyses because forecasts were not improved greatly using catch in weight (Section 5.2.2). Assuming environmental variables can be observed before a catch forecast is needed, TFN models provide appropriate means for forecasting catch with auxiliary data. Correlations between the catches and environmental data in each area were compiled prior to the analysis; these correlations (Appendix D) are referenced in several sections.

8.1 Approach

Square root transformations were applied to stabilize variance in each series. This transformation was optimal for most of the univariate series (Chapter 5) and was applied uniformly to simplify the analyses. Catch and environmental series were made equal in length by adding mean values to the beginning of short environmental series. Discussion of the benefits from and alternatives to this procedure is found in Section 7.4.

The joint multivariate identification methodology described by Liu and Hanssens (1982) was initially adopted for the analyses. Applied to the pink salmon data, eight environmental series (Tables 3.1-3.2) were considered, and impulse response weights $\{v_i\}$ were calculated to i=3. Parameters for the least significant impulse response weights were deleted one at a time until all parameters were significant (usually at $P < 0.1$). Over-parameterized and unstable models were identified by this method, as described below. Thus, two prewhitening methods and a forward selection procedure using cross-correlations between the filtered series was adopted for subsequent model building.

One prewhitening procedure used an AR filter ($\phi_1 \approx 0.3$) to remove first-order autocorrelation common to catch (Y) and environmental (X) series. A second (separate) procedure used the minimum-RMS univariate model for catch (Chapter 5) to prewhiten Y. After either procedure, cross-correlations between the filtered series were used to select a environmental series, and identify a transfer function relating catch to that variable. Finally, a noise model was identified for the disturbance series (7.4).

An iterative procedure was used to build models with more than one exogenous variable. Residuals from each adequate model were cross-correlated with the environmental data to indicate if another explanatory variable could be important. If so, new transfer functions and a noise model were sequentially identified, estimated, and checked for adequacy (Chapters 5 and 7). When a larger model was found, a sequential F-test (using the extra sum of squares principle) was sometimes made to test if adding a parameter to the model was significant ($P < 0.10$). This test was not employed if the lag structure of the competing models changed the number of data (time) over which the sum of squares would be computed. Residual variance (RMS) statistics were also used to compare models, and r^2 was reported for selected models. Note that since mean values were appended to short exogenous series, statistics for fitting model parameters and characterizing variance explained can be misleading, because degrees of freedom used may not be correct. Forecasts from the models are, however, not misleading.

Estimation of TFN models was made on a VAX 8600 computer using the conditional and "exact" likelihood functions for AR and MA parameters, respectively, in the SCA Time Series package (Liu et al. 1986). Catch and exogenous series were not centered (at mean 0), so a constant C was explicit in each model for stationary series. Significance of estimated parameters was judged, in part, on estimated t-statistics. A value of $t > t_{crit}=1.3$ ($\alpha=0.2$) was required to include any parameter, other than C, in a model. An estimated value for C was always included in a model relating stationary series.

Five estimations and one-step-ahead forecasts for each adequate model are reported, as in previous analyses. Forecasts are made by using the "exact" likelihood function for moving average parameters (Liu et al. 1986).

In a TFN model, forecasts of exogenous series are required to forecast Y. Such forecasts are made by using the minimum-RMS models described in Chapter 5, even if they might not be the "best" models for the series, as explained in Section 5.5. Forecast errors from several explanatory variables contributed to the forecast error in Y under the assumption that exogenous series are independent (Liu et al. 1986).

Considering salmon life histories and their hypothesized time-place relationships to the environment (Chapters 2 and 3), cross-correlations from 0 to 3 years before the pink salmon catch, 0 to 5 years before the chum and coho salmon catch, and 0 to 6 years before the sockeye salmon catch (Appendix D) were considered in the analyses. Environmental data at lag 0 that could not physically influence catch in year 0 was rejected from tentative identifications (e.g., Aug-Oct wind speed near Seward, Alaska in year t probably does not influence catch of pink salmon in Southeast Alaska in year t).

8.2 Results

8.2.1 Pink Salmon

Models used to prewhiten the series are described in Chapter 5; they are AR(2) models of square root transformed catches (Table 5.3). Prior to prewhitening, two correlations between transformed catch and environmental data (Table D1) at lags expected to be important (Table 3.2) were significant ($P \leq 0.05$).

Southern Southeast

No cross-correlations between either the filtered or prewhitened input and output series were significant (1.5 SE). Using the Liu-Hanssens procedure and a t-statistic of 1.5, I identified a model with 19 parameters, but rejected it on grounds of parsimony; using a t-statistic of 2.0 I identified a model with 5 parameters. The 5-parameter model collapsed (reduced to 0 significant exogenous parameters) after Nwind at lag 0 was rejected because of physical impossibility of the implied relationship (time of events).

Because a multivariate model was not found for the long-term data, the analysis was repeated with the series truncated to begin in 1951. The shortened series are probably nonstationary as illustrated in Figure 2.1 and discussed in Sections 5.3 and 7.4. Thus, the series was modeled by ARMA (1,1,0) with RMS=.085 (as discovered for catches between 1960 and 1985, Section 5.3). The Liu-Hanssens procedure again leads to an unparsimonious model. The most significant cross-correlation (1.8 SE), obtained after prewhitening by the AR(1,1,0) model, involved mean winter air temperature (SSEwint) at lag 1. RMS for the TFN model with SSEwint was 13% lower than the RMS for the univariate model.

Residuals from the model with SSEwint were most significantly correlated (1.4 SE) with June-July upwelling (SEupw) at lag 1, August-October wind speed (Nwind) at lag 1, and summer sea surface temperature at 55° N (SST55s) at lag 2. Only SEupw was significant (2 SE) when added to the TFN model with NSEwint. RMS for the model which includes NSEwint and SEupw was 27% below RMS for the univariate model (Table 8.1). The r^2 for this model was 0.49.

To see if a stationary identification for this series might be appropriate, models were also constructed assuming Z_t was stationary. The most significant cross-correlation (1.8 SE), obtained after prewhitening by a univariate AR(2) model (RMS=.0822),

Table 8.1. TFN models of square root transformed southern Southeast, northern Southeast, and Southeast Alaska **pink salmon** catch/10^7. Residual mean square error (RMS) of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each model.

Southern SE Alaska - 1951 through 1985 data[a]	RMS	Median	Mean	MPE
$(1-B)Y_t = (.24\ B)\,W1_t - (.11\ B)\,U_t + (1+.77\ B)^{-1}a_t$ (2.3) (-2.5) (-7.0)	.0623	38.9	32.2	-13.4
$Y_t = .39 + (.27\ B)\,W1_t + (.82\ B)\,N_t + (1-.84\ B^2)^{-1}a_t$ (.74) (2.6) (2.6) (5.8)	.0610	27.6	36.4	-30.9

Northern SE Alaska[a]	RMS	Median	Mean	MPE
$Y_t = .47 + (.13\ B^2)D2_t + (1-.21\ B-.40\ B^2)^{-1}a_t$ (3.0) (2.1) (1.8) (3.6)	.0655	40.0	47.4	-17.9
$Y_t = .41 + (.16\ B^2)D2_t - (.09\ B^2)U_t + (1-.24\ B-.39\ B^2)^{-1}a_t$ (2.6) (2.6) (-2.0) (2.0) (3.5)	.0619	30.4	39.5	-17.4
$Y_t = -1.3 + (.16\ B^2)D2_t - (.10\ B^2)U_t + (.24\ B)V_t + (1-.22\ B-.39\ B^2)^{-1}a_t$ (-1.6) (2.7) (-2.3) (2.1) (1.9) (3.5)	.0582	34.1	35.7	-15.3

Southeast Alaska[a]	RMS	Median	Mean	MPE
$Y_t = -2.2 + (.72\ B)E_t + (1-.20\ B-.38\ B^2)^{-1}(1+.36\ B^5)a_t$ (-1.0) (1.7) (1.7) (3.3) (-3.4)	.1210	23.6	25.0	-25.0
$Y_t = 1.1 + (.16\ B)C_t + (1-.20\ B-.43\ B^2)^{-1}(1+.37\ B^5)a_t$ (5.5) (2.0) (1.7) (3.8) (-3.4)	.1186	23.3	28.9	-25.5
$Y_t = -3.0 + (.89\ B)E_t - (.16\ B^2)U_t + (1-.44\ B^2)^{-1}(1+.63\ B^5)a_t$ (-1.8) (2.7) (-2.9) (3.9) (-6.9)	.1126	24.7	23.3	-23.3

[a] Codes: W1=SSEwint/10; N=Nwind/10; D2=NSEdis/10^5; U=SEupw/10; V=SSTave; E=SEsst/10; C=SEcold/10; see also Table 3.1.

involved mean winter air temperature (SSEwint) at lag 1. Residuals from the model with SSEwint were most significantly correlated (1.9 SE) with August-October wind speed (Nwind) at lag 1. RMS for the model which includes both NSEwint and Nwind was 26% below RMS for the AR(2) model (Table 8.1). The stationary and nonstationary identifications thus yield similar models (SSEwint and Nwind or SEupw) and forecasts. The nonstationary model produced the best forecasts.

Forecasts from the model with NSEwint and SEupw are shown in Table 8.2. The mean absolute error (MAPE) in forecasting 1981-1985 catches with this model was 13% (3.9 percentage points) *higher* than MAPE from the univariate model (Table 5.3).

Northern Southeast

Freshwater discharge (NSEdis) at lag 2 and inland SST (NSEsst) at lag 1 were the most significant variables identified from cross-correlations. A model with NSEdis provides the lowest RMS (Table 8.1, center panel) for a model with one exogenous parameter. Cross-correlating residuals from this model and the environmental series led to a model with upwelling (SEupw) at lag 2. Repeating the procedure again led to a model with Northeast Pacific SST (SSTave) at lag 1 (Table 8.1). The latter model was also obtained using the Liu-Hanssens procedure. F-tests indicated that addition of the SEupw (F=3.6) and SSTave (F=3.9) parameters were significant ($P < 0.10$).

Forecasts from the model with three environmental variables are shown in Table 8.2 (center panel, r^2=0.45). Relative to the univariate model (Table 5.3), RMS was reduced by 22%, and mean absolute error (MAPE) in forecasting catches between 1981 and 1985 was reduced 30% (15 percentage points).

Southeast Alaska

Low winter air temperature (SEcold) at lag 1, inland SST (SEsst) at lag 1, and freshwater discharge (SEdis) at lag 2 were the most significant variables identified from cross-correlations. TFN models which included either SEcold or SEsst yielded similar RMS statistics (Table 8.1, lower panel). RMS for these models was about 11% below RMS from the univariate AR(2) model (Table 5.3). Cross-correlations between both residual series and environmental data indicated that upwelling (SEupw) at lag 2 is the next most important variable. A model with SEsst and SEupw (Table 8.1) had a lower RMS than a model with SEdis and SEupw.

Using the Liu-Hanssens procedure and a t-statistic of 1.5, a model with 18 parameters was identified, but I rejected that model as unparsimonious; using a t-statistic of 2.0, no environmental variables were included in the model.

Table 8.2. Forecasts, actual catches, and relative errors of forecasts from TFN models of square root transformed **pink salmon** catches in southern (SSE), northern (NSE) and Southeast (SE) Alaska fishing areas. Catch in numbers/10^7. Model parameters (P=list) are defined in Table 8.1.

	($P=W1,U;\phi_1$) SSE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	0.376	0.823	1.445	1.347	-38.9	38.9
82	0.783	1.394	2.180	1.292	7.9	7.9
83	0.650	1.203	1.925	3.142	-61.7	61.7
84	1.038	1.813	2.803	2.090	-13.2	13.2
85	3.005	4.237	5.681	3.047	39.0	39.0
86	1.961	2.984	4.221			
				medians	-13.2	38.9
				means	-13.4	32.2

	($P=D2,U,V;\phi_1,\phi_2$) NSE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	0.163	0.505	1.035	0.536	-5.7	5.7
82	0.134	0.449	0.949	1.132	-60.3	60.3
83	0.284	0.708	1.320	0.605	17.0	17.0
84	0.255	0.657	1.246	0.490	34.1	34.1
85	0.343	0.790	1.423	2.050	-61.4	61.4
86	0.510	1.053	1.792			
				medians	-5.7	34.1
				means	-15.3	35.7

	($P=E,U;\phi_2,\theta_5$) SE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	0.773	1.741	3.098	1.897	-8.2	8.2
82	1.207	2.357	3.889	2.425	-2.8	2.8
83	0.867	1.862	3.231	3.750	-50.4	50.4
84	0.916	1.945	3.357	2.582	-24.7	24.7
85	2.086	3.534	5.360	5.099	-30.7	30.7
86	1.206	2.350	3.871			
				medians	-24.7	24.7
				means	-23.3	23.3

Forecasts from the model with SEdis and SEupw (RMS=.1126) are shown in Table 8.2 (lower panel). The value of r^2 for this model was 0.45. Relative to a univariate model (Table 5.3), RMS was reduced by 16%, and mean error (MAPE) in forecasting catches (1981-1985) was reduced by 22% (6.7 percentage points).

8.2.2 Chum Salmon

Models selected to prewhiten the chum salmon catches are described in Chapter 5 (Table 5.5); the models are characterized by seasonal parameters at lags 1 and 4. Prior to prewhitening, only two correlations between transformed catch and environmental data (Table D4) at lags expected to be important (Table 3.2) were significant ($P \leq 0.05$).

Southern Southeast

Freshwater discharge (SSEdis) at lag 4 was the most significant variable identified from cross-correlations. A TFN model with SSEdis (Table 8.3) had RMS 6% below RMS from the minimum-RMS univariate model. Several cross-correlations between the residuals and environmental data were significant at 1.3 SE (SST55s at lag 2, SSEsst at lag 4, and Nwind at lag 2). A model with SSEdis and Northeast Pacific SST at 55° N (SST55s) produced the lowest RMS for a model with 2 exogenous series; however, an F-test (F=2.6) indicated that adding SST55s to the model was not significant ($P > 0.1$).

Forecasts from the model with SSEdis are shown in Table 8.4. The r^2 for this model was 0.53. The mean absolute percentage error (MAPE) in forecasting 1981-1985 catches with this model was 4.2% (1.8 percentage points) below MAPE from the univariate model (Table 5.6).

Northern Southeast

Cross-correlations between prewhitened catch and freshwater discharge (NSEdis) at lag 4, inland SST (NSEsst) at lag 3, and Northeast Pacific SST (SST55s) at lag 3 were significant (2 SE). A model with NSEdis (Table 8.3, center panel) yielded the lowest RMS for a model with one exogenous parameter. RMS for this model was 13% below RMS from the univariate model with the lowest RMS. Residuals from the model were most significantly cross-correlated with inland SST (NSEsst) at lags 2 and 3, and with Northeast Pacific SST (SST55s) at lag 0. A model with NSEdis and NSEsst yielded the lowest RMS for a model with 2 exogenous parameters. Including NSEsst in the model lowered the RMS by an additional 16% (Table 8.3), and an F-test (F=10.1) indicated that addition of the parameter was significant ($P < 0.005$). The value of r^2 for this model was 0.69. Residuals from this model correlated significantly (2 SE) with SST55s at lag 3, but adding SST55s further lowered RMS an insignificant 2%.

Table 8.3. TFN models of square root transformed southern Southeast, northern Southeast, and Southeast Alaska **chum salmon** catch/10^6. Residual mean square error (RMS) of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each model.

Model	RMS	Median	Mean	MPE
Southern SE Alaska[a]				
$Y_t = \underset{(2.2)}{.68} + (\underset{(1.7)}{.14} B^4)D1_t + (1 - \underset{(3.0)}{.34} B - \underset{(1.5)}{.18} B^2 - \underset{(2.4)}{.26} B^4)^{-1} a_t$	.0999	28.8	41.5	+0.7
Northern SE Alaska[a]				
$Y_t = \underset{(5.3)}{.88} + (\underset{(2.2)}{.14} B^4)D2_t + (1 - \underset{(5.1)}{.54} B - \underset{(3.4)}{.40} B^4 + \underset{(-2.5)}{.31} B^5)^{-1} a_t$	.0648	39.5	29.6	+7.3
$Y_t = \underset{(4.0)}{5.8} + (\underset{(2.9)}{.16} B^4)D2_t - (\underset{(-3.4)}{.10} B^2)E2_t + (1 - \underset{(6.0)}{.60} B - \underset{(4.0)}{.44} B^4 + \underset{(-3.2)}{.37} B^5)^{-1} a_t$	.0544	23.8	21.6	-16.1
Southeast Alaska[a]				
$Y_t = \underset{(3.9)}{1.2} + (\underset{(1.9)}{.20} B^5)D_t + [(1 - \underset{(5.2)}{.54} B)(1 - \underset{(4.3)}{.44} B^4)]^{-1} a_t$	.1161	29.1	42.4	+11.2

[a] Codes: D1=SSEdis/10^5; D2=NSEdis/10^5; D=SEdis/10^5; E2=NSEsst/10; see also Table 3.1.

Table 8.4. Forecasts, actual catches, and relative errors of forecasts from TFN models of square root transformed chum salmon catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^6. Model parameters (P=list) are defined in Table 8.3.

	($P=D1;\phi_1,\phi_2,\phi_4$) SSE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	0.147	0.644	1.492	0.352	83.3	83.3
82	0.152	0.649	1.494	0.840	-22.7	22.7
83	0.143	0.627	1.452	0.514	22.1	22.1
84	0.292	0.904	1.853	1.831	-50.6	50.6
85	0.303	0.926	1.889	1.301	-28.8	28.8
86	0.428	1.131	2.169			
				medians	-22.7	28.8
				means	0.7	41.5

	($P=D2,E2;\phi_1,\phi_4,\phi_5$) NSE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	0.189	0.554	1.112	0.487	13.7	13.7
82	0.083	0.354	0.814	0.513	-30.9	30.9
83	0.259	0.663	1.253	0.671	-1.2	1.2
84	0.735	1.345	2.137	2.184	-38.4	38.4
85	0.840	1.489	2.323	1.954	-23.8	23.8
86	0.775	1.400	2.208			
				medians	-23.8	23.8
				means	-16.1	21.6

	($P=D;\phi_1,\phi_4$) SE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	0.769	1.740	3.102	0.850	104.8	104.8
82	0.405	1.166	2.318	1.359	-14.2	14.2
83	0.644	1.543	2.829	1.196	29.1	29.1
84	0.886	1.898	3.291	4.047	-53.1	53.1
85	1.598	2.920	4.639	3.267	-10.6	10.6
86	1.680	3.020	4.750			
				medians	-10.6	29.1
				means	11.2	42.4

Forecasts from model with NSEdis and NSEsst (RMS=.0544) are shown in Table 8.4 (center panel). Relative to the minimum-RMS univariate model (Table 5.5), RMS was reduced by 28% and MAPE was reduced by 39% (14 percentage points).

Southeast Alaska

Cross-correlations between prewhitened catch and freshwater discharge (SEdis) at lag 5 and inland SST (SEsst) at lag 3 were significant (2 SE). A model with SEdis (Table 8.3, lower panel) resulted in the lowest RMS for a model with one exogenous parameter. RMS for this model was 1% *greater* than RMS from the univariate model with the lowest RMS. Residuals from the TFN model with SEdis were correlated (2 SE) with inland SST (SEsst) at lag 3. However, including SEsst in the model further lowered RMS by only 3%, and an F-test (F=2.0) indicated that adding the parameter was not significant ($P > 0.1$).

Forecasts from the model with SEdis are shown in Table 8.4. The r^2 for this model was 0.63. The mean error (MAPE) in forecasting 1981-1985 catches with this model was 33% (11 percentage points) *above* MAPE from the best forecasting univariate model (Table 5.5).

8.2.3 Coho Salmon

Univariate models of square root transformed coho salmon catches in southern Southeast Alaska and logarithmic transformed catches in northern and Southeast Alaska are described in Chapter 5 (Table 5.9). A prewhitening model for square root transformed northern Southeast Alaska coho salmon catch/10^5 is ARMA(1,0,7) $\theta_{1\text{-}6}=0$, with RMS=0.2218. A prewhitening model for square root transformed Southeast Alaska coho salmon catch/10^6 is ARMA(1,0,6) $\theta_{1\text{-}5}=0$, with RMS=0.0326. Two correlations between transformed catch and environmental data (Table D5) at lags expected to be important (Table 3.2) were significant ($P \leq 0.05$).

Southern Southeast

Alongshore wind speed (Nwind) at lag 0, inland SST (SSEsst) at lag 4, and mean winter air temperature (SSEwint) at lag 4 correlated significantly with residuals from the univariate model (2 SE). TFN models with SSEsst or Nwind (Table 8.5) produced RMS statistics about 18% below RMS for the minimum-RMS univariate model. Although August-October wind speed at lag 0 was considered irrelevant to catches of pink salmon, the possibility of an association with coho salmon catches (which occur later in the year) was not rejected. Cross-correlations between the residuals of the two models and environmental data led to a model having Nwind (lag 0) and SSEwint (lag 4) as

Table 8.5. TFN models of square root transformed southern Southeast and northern Southeast **coho salmon** catch/10^5. Residual mean square error (RMS) of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each model.

Southern SE Alaska[a]	RMS	Median	Mean	MPE
$Y_t = -4.9 + (.14\,B^4)E1_t + (1 - .35\,B^2 - .21\,B^3 - .27\,B^4)^{-1} a_t$ (−2.1) (3.3) (2.6) (1.7) (2.0)	.2309	12.1	16.7	-14.6
$Y_t = 3.1 + (.17)N_t + (1 - .34\,B - .27\,B^2 - .26\,B^4)^{-1} a_t$ (5.6) (2.7) (2.8) (2.1) (2.2)	.2286	18.2	20.1	-15.0
$Y_t = .74 + (.60\,B^4)W1_t + (.16)N_t + (1 - .23\,B - .27\,B^2 - .39\,B^4)^{-1} a_t$ (0.8) (3.1) (2.8) (1.9) (2.0) (3.0)	.1977	26.9	20.5	-15.9

Northern SE Alaska[a]	RMS	Median	Mean	MPE
$Y_t = -6.1 + (.17\,B)E2_t + (1 - .48\,B + .33\,B^7)^{-1} a_t$ (−2.2) (3.1) (4.0) (−2.7)	.1874	21.9	21.0	-21.0
$Y_t = 3.1 - (.29\,B)D_t + (1 - .36\,B + .35\,B^7)^{-1} a_t$ (14.) (−3.4) (2.9) (−2.6)	.1774	27.7	28.6	-28.6
$Y_t = -4.7 - (.27\,B)D_t + (.16\,B)E2_t + (1 - .45\,B + .32\,B^7)^{-1} a_t$ (−1.9) (−3.5) (3.1) (3.8) (−2.6)	.1500	19.0	18.8	-18.8

[a] Codes: E1=SSEsst; N=Nwind; W1=SSEwint/10; E2=NSEsst; D=SEcdis/10^5; see also Table 3.1.

parameters, and to a model having Nwind (lag 0) and SSEsst (lag 4) as parameters. The model with Nwind and SSEwint (Table 8.5) fit the data best.

Forecasts from the model with SSEsst (RMS=.2309), which forecast 1981-1985 catches best, are shown in Table 8.6 (upper panel). The r^2 for this model was 0.58. The mean forecast error (MAPE) from this model (1981-1985, Table 8.6) was 9.2% (1.7 percentage points) below MAPE from the univariate forecasting model (Table 5.10).

Northern Southeast

Cross-correlations between prewhitened catch and freshwater discharge (SEcdis) at lag 1, and inland SST (NSEsst) at lags 1 and 4 were significant (2 SE). TFN models with either NSEsst (lag 1) or SEcdis (lag 1) yielded similar RMS statistics (Table 8.5, lower panel). RMS for these 2 models were, respectively, 16% and 20% below RMS from the univariate prewhitening model. Cross-correlations between the residuals (of both models) and environmental data suggested a model with both SEcdis and NSEsst. A model with both these parameters (Table 8.5) had an r^2 value of 0.45 and reduced RMS 32% over the prewhitening model. Sequential F-tests suggested the larger model was preferred to models having only NSEsst ($F=11.2$, $P < 0.005$) or SEcdis ($F=8.2$, $P < 0.01$) as exogenous variables. None of the 3 models were very stable, however: t-statistics for all parameter estimates (especially the ϕ_1 parameter), and r^2 values, dropped markedly during the 5 data-deleting estimations.

Forecasts from the TFN model with SEcdis and NSEsst are shown in Table 8.6 (center panel). Relative to the univariate forecasting model (Table 5.10), this model reduced MAPE for forecasting 1981 through 1985 catches by 49% (18 percentage points). However, part of this improvement is due to the presence of the AR(1) parameter in the multivariate model, and not in the univariate model.

Southeast Alaska

Cross-correlations between prewhitened catch and mean winter air temperature (SEwint) at lags 1 and 4, low winter air temperature (SEcold) at lags 4 and 5, freshwater discharge (SEcdis) at lag 2, and inland SST (SEsst) at lag 4 were significant at 2 SE. TFN models with catch and each variable except SEwint (at lag 1) and Secold (at lag 5) were estimated. Models with either SEcdis or SEsst as parameters (Table 8.7) yielded similar RMS statistics, which were 6% below RMS for the prewhitening model. Several cross-correlations between residuals from the 2 models and environmental data were significant at 2 SE: one significant correlation from each set of correlations is the variable of the alternative model (SEsst at lag 4 or SEcdis at lag 2). A model with both

Table 8.6. Forecasts, actual catches, and relative errors of forecasts from TFN models of square root transformed coho salmon catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^5 except SE is catch in numbers/10^6. Model parameters (P=list) are defined in Tables 8.5 and 8.7.

	(P=E1;ϕ_2,ϕ_3,ϕ_4) SSE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	3.142	5.847	9.384	6.408	-8.8	8.8
82	4.403	7.223	10.736	8.216	-12.1	12.1
83	3.526	6.299	9.871	8.662	-27.3	27.3
84	4.071	7.010	10.743	6.657	5.3	5.3
85	5.148	8.366	12.362	11.984	-30.2	30.2
86	3.715	6.516	10.099			
				medians	-12.1	12.1
				means	-14.6	16.7

	(P=D,E2;ϕ_1,ϕ_7) NSE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	2.883	4.868	7.370	6.010	-19.0	19.0
82	7.589	10.375	13.595	10.786	-3.8	3.8
83	4.391	6.732	9.573	10.180	-33.9	33.9
84	6.955	9.876	13.308	10.832	-8.8	8.8
85	5.610	8.231	11.353	11.476	-28.3	28.3
86	4.442	6.820	9.706			
				medians	-19.0	19.0
				means	-18.8	18.8

	(P=D,E;ϕ_1,θ_6) SE, Forecast Catch			Actual	Forecast Error	
yr	Lo 80%	Point	Up 80%	Catch	PE	APE
81	0.821	1.254	1.778	1.407	-10.9	10.9
82	1.171	1.674	2.267	2.138	-21.7	21.7
83	1.121	1.613	2.194	1.985	-18.7	18.7
84	1.515	2.076	2.726	1.920	8.1	8.1
85	1.428	1.971	2.601	2.540	-22.4	22.4
86	0.895	1.333	1.859			
				medians	-18.7	18.7
				means	-13.1	16.4

Table 8.7. TFN models of square root transformed Southeast Alaska coho salmon catch/10^6. Residual mean square error (RMS) of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each model.

Southeast Alaska[a]	RMS	Median	Mean	MPE
$Y_t = \underset{(11.)}{1.0} + (\underset{(2.2)}{.062}\,B^2)D_t + (1 - \underset{(4.4)}{.50}\,B)^{-1}(1 + \underset{(-5.5)}{.56}\,B^6)a_t$	.0305	28.8	23.0	-23.0
$Y_t = \underset{(-1.6)}{-1.8} + (\underset{(2.7)}{.62}\,B^4)E_t + (1 - \underset{(2.6)}{.32}\,B)^{-1}(1 + \underset{(-5.5)}{.56}\,B^6)a_t$	.0305	22.6	20.0	-17.0
$Y_t = \underset{(-2.8)}{-2.8} + (\underset{(3.2)}{.088}\,B^2)D_t + (\underset{(3.8)}{.77}\,B^4)E_t + (1 - \underset{(2.7)}{.33}\,B)^{-1}(1 + \underset{(-6.9)}{.64}\,B^6)a_t$	.0260	18.7	16.4	-13.1

[a] Codes: D=SEcdis/10^5; E=SEsst/10; see also Table 3.1.

SEcdis and SEsst reduced RMS by 20% over the prewhitening model (Table 8.7). A sequential F-test ($F=10.1$) for adding the SEcdis parameter to the SEsst model was significant ($P < 0.005$). None of these 3 models were particularly stable: t-statistics for the SEsst parameter dropped by ≈30% during the data-deleting estimations.

Forecasts from the model with SEcdis and SEsst are shown in Table 8.6. The value of r^2 for this model was 0.46. Relative to the univariate forecast model (Table 5.10), MAPE was reduced by 31% (7.3 percentage points).

8.2.4 Sockeye Salmon

The minimum-RMS univariate prewhitening models for the first differences in sockeye salmon catch in Southeast Alaska are shown in Table 5.7. These models had parameters for lag 2 (SSE), lags 1 and 2 (NSE), or lags 2 and 6 (SE). Prior to prewhitening, four correlations between transformed catch and environmental data (Table D6) at lags expected to be important (Table 3.2) were significant ($P \leq 0.05$).

Southern Southeast

Cross-correlations between prewhitened catch and inland SST (SSEsst) at lags 1 and 6, mean winter air temperature (SSEwint) at lag 1, and low winter air temperature (SSEcold) at lag 4 were significant at 1.5 SE. TFN models with SSEsst (lag 6) or with SSEcold (Table 8.8) had the lowest RMS for models with one exogenous variable; RMS for these models were 7% and 10% below RMS for the minimum-RMS univariate models.

Cross-correlations between environmental data and residuals of the model with SSEcold led to a model having SSEcold and SSEsst as parameters (Table 8.8). This model had an RMS 15% lower than RMS from the univariate prewhitening model. An F-test ($F=4.1$) for adding SSEsst to the model with SSEcold was significant ($P < 0.05$). All the models were unstable: t-statistics for the exogenous parameters in the first 2 models dropped to about 1.1 during the five data-deleting estimations, and t-statistics for the SSEcold parameter in the latter model dropped to 1.3 during the five estimations.

The best forecasts of 1981-1985 catches were obtained from the model with SSEcold and SSEsst (Table 8.8). The value of r^2 for this model was 0.60. Mean forecast error (MAPE) from this model (Table 8.9) was 10% (2.5 percentage points) below MAPE from the best forecasting univariate model (Table 5.7).

Northern Southeast

Cross-correlations between prewhitened catch and freshwater discharge (NSEdis) at lag 3, and Northeast Pacific winter SST at 50° N (SST50w) at lag 6 were significant at 1.4 SE. A model with SST50w (Table 8.8, lower panel) resulted in the lowest RMS

Table 8.8. TFN models of square root transformed southern Southeast and northern Southeast Alaska sockeye salmon catch/10^5. Residual mean square error (RMS) of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each model.

Southern SE Alaska[a]	RMS	Median	Mean	MPE
$(1-B)Y_t = -(\underset{(-1.4)}{.45}\, B^6)E1_t + (1-\underset{(4.7)}{.51}\, B^2)a_t$	.1582	16.7	25.4	-12.3
$(1-B)Y_t = (\underset{(1.6)}{.17}\, B^4)C1_t + (1-\underset{(4.5)}{.48}\, B^2)a_t$	.1532	26.9	24.8	-14.0
$(1-B)Y_t = (\underset{(1.8)}{.18}\, B^4)C1_t - (\underset{(-2.0)}{.64}\, B)E1_t + (1-\underset{(4.5)}{.49}\, B^2)a_t$	.1446	12.7	21.6	-16.6

Northern SE Alaska[a]	RMS	Median	Mean	MPE
$(1-B)Y_t = (\underset{(2.1)}{.33}\, B^6)A_t + (1-\underset{(2.4)}{.27}\, B^2+\underset{(-2.0)}{.22}\, B^6)a_t$	.1412	25.6	26.6	-16.3
$(1-B)Y_t = (\underset{(3.0)}{.49}\, B^6)A_t - (\underset{(-2.2)}{.21}\, B^6)S_t + (1-\underset{(2.3)}{.26}\, B^2+\underset{(-2.4)}{.26}\, B^6)a_t$	.1314	13.0	15.6	-8.8

[a] Codes: C1=SSEcold/10, E1=SSEsst/10, A=SST50w, S=SST55s; see also Table 3.1.

Table 8.9. Forecasts, actual catches, and relative errors of forecasts from TFN models of square root transformed sockeye salmon catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^5 except SE is catch in numbers/10^6. Model parameters (P=list) are defined in Tables 8.8 and 8.10.

yr	(P=C1,E1;θ_2) SSE, Forecast Catch Lo 80%	Point	Up 80%	Actual Catch	Forecast Error PE	APE
81	4.391	6.646	9.368	7.200	-7.7	7.7
82	3.540	5.574	8.067	8.421	-33.8	33.8
83	6.045	8.655	11.733	9.437	-8.3	8.3
84	4.934	7.298	10.122	6.476	12.7	12.7
85	3.917	6.034	8.607	11.117	-45.7	45.7
86	8.016	11.044		14.556	——	——
				medians	-8.3	12.7
				means	-16.6	21.6

yr	(P=A,S;θ_2,θ_6) NSE, Forecast Catch Lo 80%	Point	Up 80%	Actual Catch	Forecast Error PE	APE
81	0.982	2.167	3.813	2.099	3.3	3.3
82	1.212	2.490	4.222	4.389	-43.3	43.3
83	2.394	4.107	6.279	4.723	-13.0	13.0
84	2.577	4.332	6.541	4.548	-4.7	4.7
85	3.698	5.739	8.226	5.040	13.9	13.9
86	3.447	5.410	7.814		——	——
				medians	-4.7	13.0
				means	-8.8	15.6

yr	(P=A,S;ϕ_6,0_2) SE, Forecast Catch Lo 80%	Point	Up 80%	Actual Catch	Forecast Error PE	APE
81	0.714	1.039	1.425	1.080	-3.7	3.7
82	0.878	1.232	1.646	1.493	-17.5	17.5
83	1.154	1.554	2.014	1.569	-0.9	0.9
84	1.010	1.383	1.815	1.204	14.9	14.9
85	0.986	1.352	1.776	1.849	-26.9	26.9
86	1.650	2.120	2.649		——	——
				medians	-3.7	14.9
				means	-6.8	12.8

for a model with one exogenous parameter. RMS for this model was 11% below RMS from the prewhitening model. Residuals from the model with SST50w correlated significantly (1.8 SE) with Northeast Pacific summer SST at 55°N (SST55s) at lag 6. A model with both SST50w and SST55s reduced RMS by 17% over the univariate model (r^2=0.79). An F-test (F=4.8) for adding SST55s was significant ($P < 0.05$).

Mean forecast error (MAPE) from the model with SST50w and SST55s (Table 8.9, center panel) was 32% (7.2 percentage points) below MAPE from the univariate forecast model (Table 5.8).

Southeast Alaska

Cross-correlations between prewhitened catch and freshwater discharge (SEdis) at lags 3 and 5, and between prewhitened catch 5 and Northeast Pacific SST (SST50w) at lag 6, were significant at 1.5 SE. Models with either SEdis (lag 5) or SST55w (lag 6) had RMS statistics 10% and 13%, respectively, below RMS from the minimum-RMS univariate model (Table 8.10). Instability in the models was indicated by t-statistics for the SST50w parameter dropping to 1.4, and by t-statistics for the SEdis parameter dropping to 1.7 during the five data-deleting estimations.

Models with 2 exogenous parameters were identified by cross-correlating residuals from each of the one-parameter TFN models with environmental data (Table 8.10). One of these two models has parameters for SST50w and SST55s (both at lag 6) and an RMS 20% below RMS for the minimum-RMS univariate model. The r^2 for the model with SST50w and SST55s was 0.82. F-tests for adding SEdis (F=3.0) or SST55s (F=5.9) to the model with SST50w were significant ($P < 0.10$ and $P < 0.025$, respectively).

The mean error (MAPE) in forecasting 1981-1985 catches with the model having SST55s and SST50w as parameters (Table 8.9) was 33% (6.2 percentage points) below MAPE from the minimum-RMS univariate model (Table 5.7).

8.3 Discussion

Three identification procedures were employed in this study. A backward elimination procedure failed because the number of exogenous variables was so large that nonsensical combinations of many variables were found to explain variation in the data. In contrast, filtering both series by a common filter or filtering catch by its univariate model, and then adding variables one at a time led to parsimonious models. This was a logical result of considering eight exogenous series with low serial autocorrelations and a highly autocorrelated dependent variable.

Table 8.10. TFN models of square root transformed Southeast Alaska **sockeye salmon** catch/10^6. Residual mean square error (RMS) of the transformed series, the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE) are shown for each model.

Southeast Alaska[a]	RMS	Median	Mean	MPE
$(1-B)Y_t = (\underset{(2.0)}{.11}\,B^5)D_t + (1-\underset{(2.6)}{.30}\,B^6)^{-1}(1-\underset{(2.4)}{.29}\,B^2)a_t$	.0198	20.8	16.5	-13.0
$(1-B)Y_t = (\underset{(1.9)}{.10}\,B^6)A_t + (1-\underset{(3.0)}{.34}\,B^6)^{-1}(1-\underset{(3.3)}{.38}\,B^2)a_t$	.0192	21.8	17.8	-14.5
$(1-B)Y_t = (\underset{(2.1)}{.10}\,B^5)D_t + (\underset{(2.0)}{.11}\,B^6)A_t + (1-\underset{(3.2)}{.37}\,B^6)^{-1}(1-\underset{(2.0)}{.25}\,B^2)a_t$	.0183	13.9	15.5	-11.0
$(1-B)Y_t = (\underset{(2.9)}{.16}\,B^6)A_t - (\underset{(-2.5)}{.076}\,B^6)S_t + (1-\underset{(3.3)}{.37}\,B^6)^{-1}(1-\underset{(3.4)}{.40}\,B^2)a_t$	.0175	14.9	12.8	-6.8

[a] Codes: D=SEdis/10^5, A=SST50w, S=SST55s; see also Table 3.1.

Cross-correlations between catch and environmental series were typically weak, and it is clear that some model identifications are also weak. Convincing evidence of persistent (dynamic) influences of environment on catches were not observed in the cross-correlations. Thus, TFN models consist of noise models which are similar to the univariate prewhitening filters, and lagged pulses of environmental noise. Also, only 1/3 of the catch-environment relationships identified in the forecasting models occurred at lags expected to be important, and environmental variables which did enter one model did not consistently enter models for the same species in other fishing areas (Table 8.11).

Impacts of including environmental data into models for catch are illustrated by comparing percent reductions in RMS for the minimum-RMS univariate and multivariate models (i.e., $100^*(RMS_{TFN}-RMS_{UV})/RMS_{UV}$), and by comparing percent reductions and differences in MAPE between the best forecasting univariate and multivariate models. RMS from TFN models was less than RMS from the univariate models for every area and species comparison except one (Southeast Alaska chum salmon). The overall average decrease in RMS was about 19%, and typically resulted from adding 2 parameters to the models (Table 8.12). The average percent decrease in MAPE was similar (18%), although TFN model forecasts for catches of pink salmon in southern Southeast Alaska and catches of chum salmon in Southeast Alaska were worse than forecasts from the univariate models (Table 8.13). The overall average reduction in MAPE (1981 and 1985) was 5 percentage points (Table 8.14).

Annual deviations in forecasts (predicted-actual) from the TFN noise models, 1981-1985, generally followed the patterns found during the univariate analysis (Figures 5.2 and 5.3). Overall, forecasts of catch in southern Southeast Alaska are essentially unimproved by adding environmental data to the models (Table 8.14). In contrast, forecasts of catches in northern Southeast Alaska were significantly improved (13 percentage points) by adding environmental data (typically 3 parameters) to the models. Forecasts of pink, coho, and sockeye salmon catch in Southeast Alaska improved impressively, given the general failure in forecasting the catches in southern Southeast Alaska. This phenomenon was also observed in Chapter 6, when forecasts of pink salmon recruitment from stock-recruit models were compared.

Table 8.11. Summary of the environmental variables and lag relationships included in TFN models of square root transformed southern (SSE), northern (NSE), and Southeast Alaska (SE) salmon catches. Environment variables that enter the model at a lag expected to be important are shown in bold type[a].

	SSE		NSE		SE	
	series	lag	series	lag	series	lag
Pink[b]	**SSEwint**	**1**	**NSEdis**	**2**	**SEsst**	**1**
	SEupw	**1**	SEupw	2	SEupw	2
			SSTave	1		
Chum	**SSEdis**	**4**	**NSEdis**	**4**	SEdis	5
			NSEsst	2		
Coho	SSEsst	4	NSEdis	1	SEdis	2
			NSEsst	1	SEsst	4
Sockeye[c]	**SSEcold**	**4**	SST50w	6	SST50w	6
	SSEsst	1	SST55s	6	SST55s	6

[a] Tables 3.1 and 3.2 contain description of variables and expected relationships between variables.

[b] Model for SSE is for ∇Z_t.

[c] Model for each area is for ∇Z_t.

Table 8.12. Summary of the number of parameters (npar) and residual mean squares (RMS) for the minimum-RMS univariate[a] (UV) and transfer function[b] (TFN) models of square root transformed southern (SSE), northern (NSE), and Southeast Alaska (SE) salmon catches. Percent reduction in RMS (100*(RMS_{TFN}-RMS_{UV})/RMS_{UV}) for each comparison are shown in bold type. On the margin are medians of the differences in npar (mpar) and means of percent reductions in RMS ($\overline{\%RMS}$).

	SSE		NSE		SE		(mpar)
	RMS	npar	RMS	npar	RMS	npar	$\overline{\%RMS}$
TFN	.062	(4)	.058	(6)	.113	(5)	(2)
UV	.085	(3)	.074	(3)	.135	(3)	
Pink	**-27.1**		**-21.6**		**-16.3**		**-21.7**
TFN	.100	(5)	.054	(6)	.116	(4)	(1)
UV	.106	(4)	.075	(4)	.115	(4)	
Chum	**-5.7**		**-28.0**		**+0.9**		**-10.9**
TFN	.198	(6)	.150	(5)	.026	(5)	(2)
UV	.282	(3)	.222	(3)	.033	(3)	
Coho	**-29.8**		**-32.4**		**-21.2**		**-27.8**
TFN	.145	(3)	.131	(4)	.018	(4)	(2)
UV	.170	(1)	.159	(1)	.022	(2)	
Sockeye	**-14.7**		**-17.6**		**-18.2**		**-16.8**
$\overline{\%RMS}$, (mpar)	**-19.3**	(1.5)	**-24.9**	(2.5)	**-13.7**	(2)	(2) **-19.3**

[a] Minimum-RMS models in Tables 5.3, 5.5, 5.7 and 5.9, except that to insure compatibility between the estimates RMS for SSE pink salmon catch is for 1951-1985 data (Section 8.2.1), and RMS for univariate models of NSE and SE coho salmon catch is for catch$^{0.5}$ (Section 8.2.3).

[b] Minimum-RMS models in Tables 8.1, 8.3, 8.5, 8.7, 8.8 and 8.10.

Table 8.13. Summary of the number of parameters (npar) and means of five one-step-ahead relative forecast errors without regard to sign (MAPE) from the univariate[a] (UV) and transfer function[b] (TFN) forecast models for southern (SSE), northern (NSE), and Southeast Alaska (SE) salmon catches. Percent reduction in MAPE ($100*(MAPE_{TFN}-MAPE_{UV})/MAPE_{UV}$) for each comparison are shown in bold type. On the margin are medians of the differences in npar (mpar) and means of the percent reductions in MAPE ($\overline{\%MAPE}$).

	SSE		NSE		SE		(mpar)
	MAPE	npar	MAPE	npar	MAPE	npar	$\overline{\%MAPE}$
TFN	32.2	(4)	35.7	(6)	23.3	(5)	(2)
UV	28.3	(3)	50.8	(3)	30.0	(3)	
Pink	**+13.8**		**-29.7**		**-22.3**		**-12.8**
TFN	41.5	(5)	21.6	(6)	42.4	(4)	(1)
UV	43.3	(4)	35.4	(3)	31.9	(4)	
Chum	**-4.2**		**-39.0**		**+32.9**		**-3.4**
TFN	16.7	(5)	18.8	(5)	16.4	(5)	(2)
UV	18.4	(3)	36.8	(2)	23.7	(3)	
Coho	**-9.2**		**-48.9**		**-30.8**		**-29.7**
TFN	21.6	(3)	15.6	(4)	12.8	(4)	(2)
UV	24.1	(1)	22.8	(1)	19.0	(2)	
Sockeye	**-10.4**		**-31.6**		**-32.6**		**-24.9**
$\overline{\%MAPE}$, (mpar)	**-2.5**	(1.5)	**-37.3**	(3)	**-13.2**	(2)	(2) **-17.7**

[a] Models in Tables 5.3, 5.6, 5.8 and 5.10.
[b] Models in Tables 8.2, 8.4, 8.6 and 8.9.

Table 8.14. Differences between means of one-step-ahead relative forecast errors without regard to sign (MAPE) from the univariate[a] (UV) and transfer function[b] (TFN) forecast models for southern (SSE), northern (NSE), and Southeast Alaska (SE) salmon catches. Differences between means for each comparison are shown in bold type. On the margin are means of the differences in MAPE ($\overline{\text{MAPE}}$).

	MAPE			
	SSE	NSE	SE	$\overline{\text{MAPE}}$
TFN	32.2	35.7	23.3	
UV	28.3	50.8	30.0	
Pink	**+3.9**	**-15.1**	**-6.7**	**-6.0**
TFN	41.5	21.6	42.4	
UV	43.3	35.4	31.9	
Chum	**-1.8**	**-13.8**	**+10.5**	**-1.7**
TFN	16.7	18.8	16.4	
UV	18.4	36.8	23.7	
Coho	**-1.7**	**-18.0**	**-7.3**	**-9.0**
TFN	21.6	15.6	12.8	
UV	24.1	22.8	19.0	
Sockeye	**-2.5**	**-7.2**	**-6.2**	**-5.3**
$\overline{\text{MAPE}}$,	**-0.5**	**-13.5**	**-2.4**	**-5.5**

[a] Models in Tables 5.3, 5.6, 5.8 and 5.10.
[b] Models in Tables 8.2, 8.4, 8.6 and 8.9.

CHAPTER 9

MULTIVARIATE TIME SERIES THEORY: SEVERAL DEPENDENT VARIABLES

Univariate and multivariate theory for modeling one dependent time series can be extended to model several dependent series. Each dependent series in these general models may (or may not) interact with any other series in the model. Assume the notation and terminology developed in previous chapters, and consider k time series. Let the i^{th} series at time t be $\{Z_{it}\}$, and let the ($k \times 1$ column) vector $[\mathbf{Z}_{1t}, Z_{2t}, ..., Z_{kt}]^T$ be denoted by $\mathbf{Z}_t$. Then, a general vector ARMA (or VARMA) model for k mean-zero time series $\tilde{\mathbf{Z}}_t = \mathbf{Z}_t\text{-}\mathbf{U}$, $\mathbf{U} = [\mu_1, p_2, ..., \mu_k]^T$, (Tiao and Box 1981; Quenouille 1957) is

$$\underline{\phi}(B)\,\tilde{\mathbf{Z}}_t = \underline{\theta}(B)\,\mathbf{a}_t \tag{9.1}$$

where $\underline{\phi}$ and $\underline{\theta}$ are $k \times k$ matrices of finite polynomials in lag operator B:

$$\underline{\phi}(B) = (\underline{I} - \underline{\phi}_1 B - ... - \underline{\phi}_p B^p)$$

$$\underline{\theta}(B) = (\underline{I} - \underline{\theta}_1 B - ... - \underline{\theta}_q B^q)$$

$\underline{\mathbf{I}}$ is a $k \times k$ identity matrix, and $\mathbf{a}_t$ is a $k \times 1$ vector of independent Gaussian random elements a_{it}. The individual variables $\tilde{Z}_{it}$ each follow an ARMA(p,q) process which may not be the process for $\tilde{\mathbf{Z}}_t$ (see below), permitting interactions between the series. Also, $\mathbf{Z}_t$ can be used instead of $\tilde{\mathbf{Z}}_t$ in (9.1) if a $k \times 1$ vector of constants $\mathbf{C}$ is added to the right-hand side of the equation. The model may also include seasonal factors $[\underline{\Phi}(B^s)$, $\underline{\Theta}(B^s)]$ and nonstationary operators $(1\text{-}B)^d$ as needed (Chapter 4).

The VARMA model includes many different time series models. For example, consider the bivariate AR(1) process $(\underline{I} - \underline{\phi}_1 B)\tilde{\mathbf{Z}}_t = \mathbf{a}_t$

$$\left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{bmatrix} B\right) \begin{bmatrix} \tilde{Z}_{1t} \\ \tilde{Z}_{2t} \end{bmatrix} = \begin{bmatrix} a_{1t} \\ a_{2t} \end{bmatrix} \tag{9.2}$$

which implies

$$\tilde{Z}_{1t} = \phi_{11}\tilde{Z}_{1(t-1)} + \phi_{12}\tilde{Z}_{2(t-1)} + a_{1t}, \tag{9.3}$$

$$\tilde{Z}_{2t} = \phi_{21}\tilde{Z}_{1(t-1)} + \phi_{22}\tilde{Z}_{2(t-1)} + a_{2t}. \tag{9.4}$$

When all elements of $\underline{\phi}_1$ in (9.2) are non-zero, a "feedback" relationship exists between the variables, as shown. If $\underline{\phi}_1$ in (9.2) is a diagonal matrix (ϕ_{12} *and* ϕ_{21} = 0) then unrelated univariate relationships are implied. If $\underline{\phi}_1$ in (9.2) is triangular (ϕ_{12} *or* ϕ_{21} = 0) then a one-directional relationship exists between $\tilde{Z}_{1t}$ and $\tilde{Z}_{2t}$. In this case, if ϕ_{12}=0 then (9.4) is unchanged but (9.3) becomes

$$\tilde{Z}_{1t} = \phi_{11}\tilde{Z}_{1(t-1)} + a_{1t} \tag{9.5}$$

and the bivariate model (9.2) can be reduced to a transfer function-noise model (Wei 1990, p. 338-339).

Coefficient matrices in a VARMA model (9.1) may also be partitioned in varied ways to permit modeling of relationships between <u>sets</u> of variables. For example, one-directional relationships exist between two sets of variables when coefficient matrices are block-triangular. Consider a block-triangular VARMA(1,0) model with $\tilde{\mathbf{Z}}_{1t}$ = $[\tilde{Y}_{1t},\tilde{Y}_{2t}]^T$, $\mathbf{a}_{1t} = [a_{1t},a_{2t}]^T$, $\tilde{\mathbf{Z}}_{2t} = [\tilde{X}_{1t},\tilde{X}_{2t}]^T$, $\mathbf{a}_{2t} = [e_{1t},e_{2t}]^T$. Now, if $\underline{\phi}_{21}$ matrix in $\underline{\phi}_1$ is $\underline{0}$

$$\left(\begin{bmatrix} \underline{I} & \underline{0} \\ \underline{0} & \underline{I} \end{bmatrix} - \begin{bmatrix} \underline{\phi}_{11} & \underline{\phi}_{12} \\ \underline{0} & \underline{\phi}_{22} \end{bmatrix} B \right) \begin{bmatrix} \tilde{\mathbf{Z}}_{1t} \\ \tilde{\mathbf{Z}}_{2t} \end{bmatrix} = \begin{bmatrix} \mathbf{a}_{1t} \\ \mathbf{a}_{2t} \end{bmatrix}$$

the X (say environment) series may influence Y (say catch) series, there may be feedback between Y, or between X variables, but Y cannot influence X. In general, $\underline{\phi}_i B^i$ i = 1,2,..p, and $\underline{\theta}_j B^j$ j = 1,2,..,q in (9.1) may be partitioned in many different ways.

Vector AR models are stationary if the roots of the determinantal AR polynomial det[$\underline{\phi}$(B)] are outside the unit circle (> 1 in absolute value). Similarly, MA models are invertible if the roots of det[$\underline{\theta}$(B)] are > 1 in absolute value (Tiao and Box 1981). Both conditions apply for vector ARMA models (see Wei 1990).

9.1 Model Identification

Modeling usually begins by transforming any nonstationary series into a stationary series. Tentative identification of a VARMA(0,q) can be made by examining matrices of sample cross-correlations $\underline{\rho}(\mathcal{L})=\{\rho_{ij}(\mathcal{L})\}$ for lags $\mathcal{L}$ =1,2,..,m

$$\rho_{ij}(\mathcal{L}) = \frac{\sum_{t=\mathcal{L}+1}^{n} (Z_{it}-\bar{Z}_i)(Z_{j(t-\mathcal{L})}-\bar{Z}_j)}{\left[\sum_{t=1}^{n} (Z_{it}-\bar{Z}_i)^2 \sum_{t=1}^{n} (Z_{jt}-\bar{Z}_j)^2\right]^{1/2}} \tag{9.6}$$

where $\bar{Z}_i$ is the sample mean for the i^{th} series. Tiao and Box (1981) suggest $\pm 2/\sqrt{n}$ to gauge significance of $\rho_{ij}(\mathcal{L})$. Then, if $\tilde{Z}_t$ follows a VARMA(0,q) model, $\underline{\rho}(\mathcal{L})=0$ for $\mathcal{L}>q$; thus, low-order vector MA(q) models may be identified from the cutting-off property of significant correlations, as for univariate models. For example, a bivariate VARMA(0,2) process might yield

$$\begin{array}{c} \underline{\rho}(\mathcal{L}) \\ \text{for} \\ \mathcal{L}=1\text{-}5 \end{array} \quad \begin{bmatrix} - & \cdot \\ \cdot & - \end{bmatrix} \begin{bmatrix} + & \cdot \\ + & + \end{bmatrix} \begin{bmatrix} \cdot & \cdot \\ \cdot & \cdot \end{bmatrix} \begin{bmatrix} \cdot & \cdot \\ \cdot & \cdot \end{bmatrix} \begin{bmatrix} \cdot & \cdot \\ \cdot & \cdot \end{bmatrix}$$

where the indicator symbols +, -, and $\cdot$ are used to denote significant positive, significant negative, or non-significant ρ_{ij}, respectively, when series j leads series i.

Tentative identification of VARMA(p,0) models may be made from matrices of sample partial autoregression coefficients $\underline{\mathcal{P}}(\mathcal{L})=\underline{\phi}_{\mathcal{L}}$. $\underline{\mathcal{P}}(\mathcal{L})$ is defined as the last parameter matrix obtained in successive fittings of

$$\mathbf{Z}_t = \mathbf{C} + \underline{\phi}_1 \mathbf{Z}_{t-1} + \ldots + \underline{\phi}_{\mathcal{L}} \mathbf{Z}_{t-\mathcal{L}} + \mathbf{a}_t$$

with least squares, for $\mathcal{L}=1,2,\ldots,m$ (Box and Tiao 1981). The significance of ϕ_{ij} are judged from their standard errors. If $\tilde{Z}_t$ follows a VARMA(p,0) model, then $\underline{\mathcal{P}}(\mathcal{L})=0$ for $\mathcal{L}>p$; thus vector AR(p) models may be identified by a cutting-off of significant partial autoregression matrices, as for univariate models. To test the hypothesis $H_0{:}\underline{\mathcal{P}}(\mathcal{L})=0$ versus $H_a{:}\underline{\mathcal{P}}(\mathcal{L})\neq 0$, Tiao and Box (1981) employ a likelihood ratio statistic

$$M(\mathcal{L}) = -(N - \frac{1}{2} - \mathcal{L}k)\ \ln\left[\frac{|S(\mathcal{L})|}{|S(\mathcal{L}-1)|}\right] \tag{9.7}$$

where $S(\mathcal{L})$ is the determinant of the matrix of residual sums of squares and cross-products after fitting an AR($\mathcal{L}$) model, and N is the number of effective degrees of freedom (n-p-1). $M(\mathcal{L})$ is asymptotically distributed as χ^2 with k^2 degrees of freedom. For example, a bivariate VARMA(2,0) process might yield

$$
\begin{array}{cccccc}
\underline{\rho}(\mathcal{L}) \text{ for } \mathcal{L}=1\text{-}5 & \begin{bmatrix} + & \cdot \\ + & + \end{bmatrix} & \begin{bmatrix} + & \cdot \\ + & \cdot \end{bmatrix} & \begin{bmatrix} \cdot & \cdot \\ \cdot & \cdot \end{bmatrix} & \begin{bmatrix} \cdot & \cdot \\ - & + \end{bmatrix} & \begin{bmatrix} \cdot & \cdot \\ \cdot & \cdot \end{bmatrix} \\
M(\mathcal{L}) & 37. & 39. & 3.9 & 12. & 6.5
\end{array}
$$

(where indicator symbols are used as before) indicating the AR(2), or more complicated, model since $\chi^2_{4,\,01} = 13$.

Vector ARMA(p,q) models may be tentatively identified from cutting-off properties of the cross-correlation matrices $\underline{\rho}(\mathcal{L})$ of residuals obtained from autoregressive fittings of the data. However, if the model is VARMA(p,q), estimates of $\underline{\rho}(\mathcal{L})$ are biased (since residuals are correlated) and may be misleading in choosing q. To avoid this problem, and to include nonstationary series in an analysis, other algorithms have been proposed to aid in the identification of VARMA(p,q) models (Tiao and Tsay 1983; Tsay and Tiao 1985; Newbold 1988; Tiao and Tsay 1989).

In contrast to univariate processes, some vector processes can be represented by both finite order AR and MA forms, and thus the identifications may not be unique. Wei (1990) illustrates this with an example and suggests final model form may depend on the purpose of the study.

9.2 Estimation and Diagnostic Checking

Conditional and exact likelihood expressions are maximized to estimate parameters (Tiao and Box 1981; Wei 1990). Diagnostic checking is similar to the univariate situation; i.e, checking for residual correlations and stationarity (or invertibility) of the model.

Model parsimony is also important in building vector ARMA models. Parameter estimates that are not significant with 100(1-alpha)% confidence are traditionally constrained to be 0.0, and the model is re-estimated. Diagonal elements of the residual covariance matrix Σ are tabulated to see how model fit improves as parameters are added to a model.

If a tentatively identified model is stationary and/or invertible, cross-correlations $\underline{\rho}(\mathcal{L})$ of the residual series are computed to check for model adequacy. Only a small fraction of the computed correlations will be significant due to chance alone.

Contemporaneous relationships among individual series in $\mathbf{Z}_t$ are reflected in Σ

(Tiao and Tsay 1983); these correlations (f_{ij}, say) are estimated from elements of Σ

$$[f_{ij}] = \frac{\mathrm{cov}(i,j)}{\mathrm{var}(i)^{1/2} \cdot \mathrm{var}(j)^{1/2}}$$

and may be useful in understanding the structural relationships between series.

Several eigenvalue and eigenvector analyses have also been suggested. Box and Tiao (1977) suggest that the lag 0 cross-correlation matrix $\underline{\rho}(0)$ be inspected for zero or near zero eigenvalues to expose **exact** contemporaneous relationships between the time series. Such relations cause singularities which can be resolved by removing a dependent relationship defined by the indicated eigenvector. Similar but lagged relations between the data are found from eigenvalues of Σ obtained after AR models are fit to $\mathbf{Z}_t$ (Liu 1986). It is, however, hard to imagine a situation in fisheries where exact contemporaneous relations between time series could occur.

The application of the vector ARMA techniques to fisheries is rare. Cohen and Stone (1987) and Stone and Cohen (1990) modeled data for six species in Lake Superior to describe their interactions and to forecast catch and abundance. Mendelssohn and Cury (1987) used vector ARMA techniques to model and forecast catch per unit effort (CPUE) of pelagic species from its own past CPUE and sea surface temperatures.

CHAPTER 10

MULTIVARIATE TIME SERIES MODELS: SEVERAL DEPENDENT VARIABLES

Pacific salmon share spatial and temporal environments during their life cycle, and interactions between the species are likely. If these interactions significantly influence abundance they almost surely influence numbers of salmon caught, and models which examine the interactions may yield improved forecasts of catch.

The first part of this chapter (Sections 10.1 and 10.2) describes catches of pink, chum, coho, and sockeye salmon in Southeast Alaska as a single, related system. Vector ARMA models for the four variables are developed to forecast the catches in each management area, and the results are compared to results presented earlier, which consider the catches as independent, unrelated series. The second part of the chapter (Sections 10.3 and 10.4) considers models where correlations suggesting feedback are present between catches of different species, and environmental data are included in the model. This later analysis illustrates the significant difficulties involved in identifying multivariate time series models for related fisheries and oceanography data.

10.1 Approach to Modeling Catch Data

Series of pink, chum, sockeye, and coho salmon catches within fishing areas of Southeast Alaska (Tables A1-A3) were made equal in length by starting each series on the year the shortest series began. Thus, 57, 58, and 68 years of data were used to model catches ($\mathbf{Z}_t$) in southern, northern, and Southeast Alaska, respectively. Square root transformations were used to stabilize variance in the series. Contemporaneous (lag $\mathcal{L}$=0) correlations between series usually increased due to this transformation (Table E1).

Matrices of cross-correlation $\underline{\rho}(\mathcal{L})$ and partial autoregression $\underline{\mathcal{P}}(\mathcal{L})$ coefficients, and M($\mathcal{L}$) statistics, to $\mathcal{L}$=6, were employed to identify tentative autoregressive (AR), moving average (MA), or mixed (ARMA) models for the transformed series (Chapter 9). When an AR model was indicated, matrices of residual cross-correlations from fitting the AR model were inspected for cutting-off patterns suggestive of an ARMA(p,q) model.

Estimations began by jointly estimating all parameters in the tentative model. A vector of constants C was explicitly included in models since $\mathbf{Z}_t$ was constructed from observed data. All parameters (except C) not significant at 1.5 SE were then set to 0, and an iterative process of estimation and checking was used to eliminate parameter estimates not significant at 2 SE, and obtain a parsimonious model. Constants **C** were dropped from models for nonstationary data ($\nabla \mathbf{Z}_t$) if they were not significant at 2 SE.

Autocorrelations in and cross-correlations between residual series ($\mathbf{a}_t$) were computed to $\mathcal{L}$=6 to investigate model adequacy. Stationarity and invertibility of the estimated models was determined from roots of the determinantal polynomials of the estimated models.

Five estimations and one-step-ahead forecasts of catch (1981-1986) from final models are reported as in previous analysis. All computations were made on a VAX 8600 computer using the SCA Statistical System (Liu et al. 1986), with the "exact" likelihood function being used to estimate moving average parameters.

10.2 Models of Pink, Chum, Sockeye, and Coho, Salmon Catch

Persistent cross-correlations between the transformed series within each management area (southern, northern, or Southeast Alaska) suggested that low-order moving average models were not appropriate for modeling these series (Tables 10.1-10.3). Also, M($\mathcal{L}$) statistics were significant at lags 1, 2, and 4 in each management area (compare M to $\chi^2_{16,\,0.05}$ = 26, Tables 10.1-10.3). Autoregressive models for catches in each area could thus be autoregressive, with $\mathcal{L}$=1,..,4. Vector AR(4) models

$$(\underline{\mathbf{I}} - \underline{\phi}_1 B - \underline{\phi}_2 B^2 - \underline{\phi}_3 B^3 - \underline{\phi}_4 B^4)\, \mathbf{Z}_t = \mathbf{C} + \mathbf{a}_t \qquad (10.1)$$

were therefore fit to the series, and found to adequately describe $\mathbf{Z}_t$, as shown below.

The first differences of each series ($\nabla \mathbf{Z}_t$) were also modeled, since the series may be nonstationary (Chapter 5). Cross-correlations between the differenced series alternate between positive and negative, and are not clearly cut-off, suggesting an AR process. M($\mathcal{L}$) statistics were significant through lag 3 (Tables 10.4-10.6). A mixed vector ARMA process could be inferred from the slow decay of significant cross-correlation $\underline{\rho}(\mathcal{L})$ and partial autoregression $\underline{\mathcal{P}}(\mathcal{L})$ coefficients. Also, a vector MA(2) or MA(3) model could be inferred by assuming the significant cross-correlations $\underline{\rho}(\mathcal{L})$ *are* cut-off at lag $\mathcal{L}$=2 or $\mathcal{L}$=3. However, given significant M($\mathcal{L}$) statistics to $\mathcal{L}$=3, and slow decay in the coefficients of $\underline{\rho}(\mathcal{L})$, vector AR(3) models for $\nabla \mathbf{Z}_t$

$$(\underline{\mathbf{I}} - \underline{\phi}_1 B - \underline{\phi}_2 B^2 - \underline{\phi}_3 B^3)\, (\underline{\mathbf{I}} - B)\, \mathbf{Z}_t = \mathbf{C} + \mathbf{a}_t \qquad (10.2)$$

Table 10.1. Cross-correlation, partial autoregression, and other statistics for modeling square root transformed southern Southeast Alaska salmon catches 1929-1985. $\mathbf{Z}_t$ = [pink/10^7, chum/10^6, sock/10^5, coho/10^5]^T.

Cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$\mathcal{L} = 1$	2	3	4	5	6
$\begin{bmatrix} + & + & + & + \\ + & + & + & + \\ + & + & + & + \\ + & + & + & + \end{bmatrix}$	$\begin{bmatrix} + & + & + & + \\ + & + & + & + \\ + & \cdot & + & \cdot \\ + & + & + & + \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & + \\ + & + & + & + \\ + & \cdot & + & \cdot \\ + & + & + & + \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & + \\ + & + & + & + \\ + & \cdot & + & \cdot \\ + & + & + & + \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & + \\ + & \cdot & + & \cdot \\ + & + & + & + \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & + \\ \cdot & \cdot & \cdot & \cdot \\ + & + & + & + \end{bmatrix}$

Partial autoregression coefficients[a] ($\wp_{ij}$), M, and residual variances (Σ), at lag $\mathcal{L}$

$\mathcal{L}$	$\wp_{ij}$	M	Σ
1	$\begin{bmatrix} \cdot & \cdot & + & \cdot \\ \cdot & + & \cdot & \cdot \\ + & \cdot & + & - \\ \cdot & \cdot & + & + \end{bmatrix}$	91.4	0.106 0.0826 0.128 0.275
2	$\begin{bmatrix} + & \cdot & \cdot & \cdot \\ + & + & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \end{bmatrix}$	42.5	0.0800 0.0423 0.110 0.223
3	$\begin{bmatrix} \cdot & \cdot & + & \cdot \\ \cdot & \cdot & + & \cdot \\ \cdot & \cdot & + & \cdot \\ - & \cdot & \cdot & + \end{bmatrix}$	18.8	0.0688 0.0380 0.0936 0.186
4	$\begin{bmatrix} \cdot & \cdot & + & + \\ \cdot & + & + & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & + & \cdot \end{bmatrix}$	39.3	0.0471 0.0198 0.0884 0.138
5	$\begin{bmatrix} \cdot & \cdot & \cdot & - \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	12.2	0.0422 0.0188 0.0791 0.110

[a] Indicator symbols +, -, and • denote significant positive, significant negative, or non-significant values (ρ_{ij} or $\wp_{ij}$, ±2 SE), when series j leads series i.

Table 10.2. Cross-correlation, partial autoregression, and other statistics for modeling square root transformed northern Southeast Alaska salmon catches 1928-1985. $\mathbf{Z}_t = [\text{pink}/10^7, \text{chum}/10^6, \text{sock}/10^5, \text{coho}/10^5]^T$.

Cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$$
\begin{array}{cccccc}
\mathcal{L}=1 & 2 & 3 & 4 & 5 & 6 \\
\begin{bmatrix} + & + & + & \cdot \\ + & + & + & \cdot \\ + & + & + & \cdot \\ \cdot & \cdot & \cdot & + \end{bmatrix} &
\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & + \\ + & + & + & \cdot \\ \cdot & \cdot & \cdot & + \end{bmatrix} &
\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & \cdot \\ + & + & + & \cdot \\ \cdot & - & \cdot & \cdot \end{bmatrix} &
\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & \cdot \\ + & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \end{bmatrix} &
\begin{bmatrix} + & \cdot & + & \cdot \\ + & \cdot & + & \cdot \\ + & \cdot & \cdot & \cdot \\ \cdot & \cdot & - & \cdot \end{bmatrix} &
\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ + & \cdot & + & \cdot \\ \cdot & \cdot & + & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}
\end{array}
$$

Partial autoregression coefficients[a] ($\wp_{ij}$), M, and residual variances (Σ), at lag $\mathcal{L}$

$\mathcal{L}$	$\wp_{ij}$	M	Σ
1	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & + & \cdot & \cdot \\ + & \cdot & + & \cdot \\ \cdot & \cdot & \cdot & + \end{bmatrix}$	61.0	0.0746 0.0776 0.104 0.237
2	$\begin{bmatrix} + & \cdot & + & \cdot \\ + & \cdot & \cdot & + \\ + & + & - & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	61.9	0.0583 0.0335 0.0774 0.221
3	$\begin{bmatrix} \cdot & - & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \end{bmatrix}$	21.3	0.0496 0.0261 0.0755 0.189
4	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ - & + & \cdot & \cdot \\ \cdot & \cdot & - & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	27.9	0.0463 0.0180 0.0598 0.186
5	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \end{bmatrix}$	13.9	0.0416 0.0158 0.0542 0.166

[a] Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values (ρ_{ij} or $\wp_{ij}$, ± 2 SE), when series j leads series i.

Table 10.3. Cross-correlation, partial autoregression, and other statistics for modeling square root transformed Southeast Alaska salmon catches 1918-1985. $Z_t = [\text{pink}/10^7, \text{chum}/10^6, \text{sock}/10^6, \text{coho}/10^6]^T$.

Cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$\mathcal{L} = 1$	2	3	4	5	6
$\begin{bmatrix} + & + & + & + \\ + & + & + & + \\ + & + & + & + \\ + & + & + & + \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & + \\ + & + & + & + \\ + & + & \cdot & + \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & + \\ + & \cdot & + & \cdot \\ + & \cdot & \cdot & + \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & + \\ + & \cdot & + & \cdot \\ + & \cdot & + & + \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & + \\ + & \cdot & + & \cdot \\ + & \cdot & + & \cdot \end{bmatrix}$	$\begin{bmatrix} + & \cdot & + & \cdot \\ + & + & + & + \\ \cdot & \cdot & + & \cdot \\ + & + & + & + \end{bmatrix}$

Partial autoregression coefficients[a] (ϱ_{ij}), M, and residual variances (Σ), at lag $\mathcal{L}$

$\mathcal{L}$	ϱ_{ij}	M	Σ
1	$\begin{bmatrix} \cdot & \cdot & + & \cdot \\ \cdot & + & \cdot & \cdot \\ + & \cdot & + & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	78.3	0.133 0.119 0.0190 0.0406
2	$\begin{bmatrix} + & \cdot & \cdot & - \\ + & + & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \end{bmatrix}$	51.6	0.0980 0.0625 0.0162 0.0346
3	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & + \end{bmatrix}$	12.1	0.0906 0.0601 0.0154 0.0286
4	$\begin{bmatrix} \cdot & \cdot & \cdot & + \\ - & + & \cdot & \cdot \\ \cdot & \cdot & - & + \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	38.7	0.0734 0.0380 0.0113 0.0256
5	$\begin{bmatrix} + & + & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	15.4	0.0570 0.0312 0.0107 0.0234

[a] Indicator symbols +, -, and • denote significant positive, significant negative, or non-significant values (ρ_{ij} or ϱ_{ij}, ±2 SE), when series j leads series i.

Table 10.4. Cross-correlation, partial autoregression, and other statistics for modeling **first differences of square root transformed southern Southeast Alaska salmon catches 1929-1985. $\mathbf{Z_t}$ = [pink/10^7, chum/10^6, sock/10^5, coho/10^5]^T.**

Cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$\mathcal{L} = 1$	2	3	4	5	6
$\begin{bmatrix} - & \cdot & \cdot & - \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ - & \cdot & \cdot & - \end{bmatrix}$	$\begin{bmatrix} + & \cdot & \cdot & \cdot \\ + & + & \cdot & + \\ \cdot & \cdot & - & \cdot \\ + & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & - \\ \cdot & \cdot & \cdot & \cdot \\ - & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & + & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & + & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$

Partial autoregression coefficients[a] ($\wp_{ij}$), M, and residual variances (Σ), at lag $\mathcal{L}$

$\mathcal{L}$	$\wp_{ij}$	M	Σ
1	$\begin{bmatrix} - & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & + & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	67.8	0.0910 0.0742 0.161 0.260
2	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ + & \cdot & - & \cdot \\ \cdot & \cdot & - & \cdot \\ + & \cdot & \cdot & - \end{bmatrix}$	32.2	0.0782 0.0537 0.139 0.214
3	$\begin{bmatrix} \cdot & \cdot & - & \cdot \\ + & - & - & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & - & \cdot \end{bmatrix}$	37.1	0.0625 0.0293 0.132 0.187
4	$\begin{bmatrix} \cdot & \cdot & \cdot & + \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & + \end{bmatrix}$	18.2	0.0500 0.0262 0.121 0.158
5	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ + & \cdot & + & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	15.4	0.0465 0.0255 0.0915 0.143

a Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values (ρ_{ij} or $\wp_{ij}$, ± 2 SE), when series j leads series i.

Table 10.5. Cross-correlation, partial autoregression, and other statistics for modeling **first differences** of square root transformed **northern Southeast Alaska** salmon catches 1928-1985. $Z_t = [\text{pink}/10^7, \text{chum}/10^6, \text{sock}/10^5, \text{coho}/10^5]^T$.

Cross-correlations[a] (ρ_{ij}) at lag ℓ

$$
\begin{array}{cccccc}
\ell = 1 & 2 & 3 & 4 & 5 & 6 \\
\begin{bmatrix} - & \cdot & \cdot & \cdot \\ - & \cdot & \cdot & - \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & - \end{bmatrix} &
\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & + \\ + & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} &
\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ - & - & \cdot & \cdot \end{bmatrix} &
\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & + & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} &
\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} &
\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & + \end{bmatrix}
\end{array}
$$

Partial autoregression coefficients[a] ($\wp_{ij}$), M, and residual variances (Σ), at lag ℓ

ℓ	$\wp_{ij}$	M	Σ
1	$\begin{bmatrix} - & \cdot & - & \cdot \\ - & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & - \end{bmatrix}$	51.5	0.0680 0.0754 0.132 0.273
2	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & + \\ \cdot & + & - & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	39.2	0.0588 0.0558 0.0999 0.234
3	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ + & - & \cdot & + \\ \cdot & + & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	43.0	0.0579 0.0259 0.0825 0.214
4	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & - & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	16.4	0.0546 0.0239 0.0677 0.198
5	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	9.3	0.0528 0.0211 0.0642 0.188

a Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values (ρ_{ij} or $\wp_{ij}$, ±2 SE), when series j leads series i.

Table 10.6. Cross-correlation, partial autoregression, and other statistics for modeling **first differences of square root transformed Southeast Alaska salmon catches 1918-1985. Z_t = [pink/10^7, chum/10^6, sock/10^6, coho/10^6]^T.**

Cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$\mathcal{L} = 1$	2	3	4	5	6
$\begin{bmatrix} - & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ - & \cdot & \cdot & - \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & + \\ \cdot & \cdot & - & \cdot \\ + & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ - & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & + & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & + \\ \cdot & \cdot & + & \cdot \\ \cdot & \cdot & \cdot & + \end{bmatrix}$

Partial autoregression coefficients[a] ($\wp_{ij}$), M, and residual variances (Σ), at lag $\mathcal{L}$

$\mathcal{L}$	$\wp_{ij}$	M	Σ
1	$\begin{bmatrix} - & \cdot & \cdot & + \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & - \end{bmatrix}$	64.3	0.123 0.141 0.0254 0.0403
2	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \\ \cdot & \cdot & - & \cdot \\ + & \cdot & \cdot & - \end{bmatrix}$	34.4	0.116 0.119 0.0213 0.0325
3	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ + & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	41.0	0.0961 0.0657 0.0211 0.0293
4	$\begin{bmatrix} - & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & - & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	23.8	0.0808 0.0618 0.0192 0.0286
5	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & + & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	11.8	0.0791 0.0542 0.0181 0.0267

a Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values (ρ_{ij} or $\wp_{ij}$, ± 2 SE), when series j leads series i.

were fit to the data, and found to provide adequate models for catches in each management area of Southeast Alaska. Results from both models (10.1 and 10.2) are thus compared by fishing area, as in previous analyses.

Southern Southeast Alaska

The AR(4) model (10.1) was fit to $\mathbf{Z}_t$, and cross-correlations between the residual series were computed to lag 6. Since only two residual correlations $\rho_{ij}(\mathcal{L})$ were significant (at $\mathcal{L}$=3 and $\mathcal{L}$=4, ±2 SE), parameter matrices for moving average terms were not added to the model. Three additional estimations were made to arrive with a model having 14 parameters (excluding the 4 constants in C) significant at 2 SE (Table 10.7).

Only 3 of 96 cross-correlations between residual series from the final estimation (3%) were significant at 2 SE (Table 10.7) suggesting an adequate fit to the data. Also, the roots of the AR polynomial are outside the unit circle, so the model is stationary. Many off-diagonal elements of the parameter matrices (Table 10.7) are significantly different from zero, leading to a very complicated model with many interactions. In particular, the model for the square root transformed series relate pink (Pk), chum (Cm), sockeye (So), and coho (Co) salmon catches:

$$Pk_t = c + \alpha_2 Pk_{t-2} - \alpha_2 Co_{t-2} + \alpha_4 So_{t-4} + a_{1t} \quad (10.3)$$

$$Cm_t = c + \beta_1 Pk_{t-1} + \beta_2 Pk_{t-2} - \beta_3 So_{t-3} + \beta_4 Cm_{t-4} + \beta_4 So_{t-4} + a_{2t} \quad (10.4)$$

$$So_t = c + \gamma_1 So_{t-1} + \gamma_2 Pk_{t-2} - \gamma_2 Cm_{t-2} + a_{3t} \quad (10.5)$$

$$Co_t = c + \delta_1 Co_{t-1} + \delta_2 Pk_{t-2} + \delta_4 So_{t-4} + a_{4t} \quad (10.6)$$

where c, and α_x, β_x, γ_x, and δ_x are, respectively, appropriate elements of C and the $\underline{\phi}_x$ matrices in Table 10.7. The residual correlation matrix

$$\begin{bmatrix} 1.00 & & & \\ -0.09 & 1.00 & & \\ 0.21 & 0.11 & 1.00 & \\ 0.56 & 0.05 & 0.12 & 1.00 \end{bmatrix}$$

confirms a moderate contemporaneous relation between pink and coho salmon catches (r=0.56), while other correlations at lag 0 are weak.

Some elements of the fitted equations (10.3-10.6) are similar to the ARMA and TFN models discovered in Chapter 5 and Chapter 8: pink salmon catch is strongly related to itself at t-2 (ϕ_2=0.76); chum salmon catch is related to itself at t-4 (ϕ_4=0.43);

Table 10.7. Parameter estimates and residual statistics for the vector AR(4) model of square root transformed pink, chum, sockeye, and coho salmon catches in southern Southeast Alaska, 1929-1985. $\mathbf{Z}_t$ = [pink/10^7, chum/10^6, sock/10^5, coho/10^5]^T.

	Estimates	Standard Errors	Diagonals of Σ
C	$[+0.10\ \ -0.14\ \ +0.57\ \ +0.18]^T$	$[0.16\ \ 0.11\ \ 0.21\ \ 0.26]^T$	$\begin{bmatrix} 0.070 \\ 0.032 \\ 0.139 \\ 0.186 \end{bmatrix}$
$\underline{\Phi}_1$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ +.20 & \cdot & \cdot & \cdot \\ \cdot & \cdot & +.70 & \cdot \\ \cdot & \cdot & \cdot & +.23 \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ .07 & \cdot & \cdot & \cdot \\ \cdot & \cdot & .10 & \cdot \\ \cdot & \cdot & \cdot & .08 \end{bmatrix}$	
$\underline{\Phi}_2$	$\begin{bmatrix} +.76 & \cdot & \cdot & -.21 \\ +.50 & \cdot & \cdot & \\ +.46 & -.32 & \cdot & \cdot \\ +.80 & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} .13 & \cdot & \cdot & .06 \\ .08 & \cdot & \cdot & \cdot \\ .17 & .14 & \cdot & \cdot \\ .17 & \cdot & \cdot & \cdot \end{bmatrix}$	
$\underline{\Phi}_3$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & -.25 & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & .07 & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	
$\underline{\Phi}_4$	$\begin{bmatrix} \cdot & \cdot & +.33 & \cdot \\ \cdot & +.43 & +.26 & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & +.46 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & .07 & \cdot \\ \cdot & .07 & .07 & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & .11 & \cdot \end{bmatrix}$	

Residual cross-correlations[a] (ρ_{ij}) at lag $\underline{\ell}$

$\underline{\ell} = 1$	2	3	4	5	6
$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & + \\ - & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$

[a] Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values of ρ_{ij} ($\pm$2 SE), when series j leads series i.

sockeye salmon catch is strongly related to itself at t-1 (ϕ_1=0.70), and; coho salmon catch is weakly related to itself at t-1 (ϕ_2=0.23). Also, three feedback relationships are obvious in the model. Pink salmon catch in (10.3) is negatively related to coho salmon catch at t-2, while coho salmon catch in (10.6) is directly related to pink salmon catch two years before. A similar relationship exists between catches of pink and sockeye salmon, while a more complicated relation between catches of chum and sockeye salmon is indicated.

The AR(3) model for $\nabla \mathbf{Z}_t$ (10.2) was fit to the data in four estimation steps, yielding a stationary model with 16 parameters and no constants (overall trend), and only one significant residual cross-correlation to lag 6 (Table 10.8). The model has feedback relationships between pink, coho, and sockeye salmon catches:

$$\nabla Pk_t = -\alpha_1 \nabla Pk_{t-1} - \alpha_2 \nabla Co_{t-2} - \alpha_3 \nabla So_{t-3} + a_{1t} \tag{10.7}$$

$$\nabla Co_t = -\delta_1 \nabla Co_{t-1} + \delta_2 \nabla Pk_{t-2} - \delta_2 \nabla Co_{t-2} - \delta_3 \nabla So_{t-3} + a_{4t} \tag{10.8}$$

and a residual correlation matrix

$$\begin{bmatrix} 1.00 & & & \\ 0.07 & 1.00 & & \\ 0.12 & 0.15 & 1.00 & \\ 0.61 & 0.24 & 0.16 & 1.00 \end{bmatrix}$$

which are similar to those described by the AR(4) model of $\mathbf{Z}_t$. Equations describing changes in chum and sockeye salmon catches can be deduced from Table 10.8 but do not add further insight to the relationships.

The AR(3) model for $\nabla \mathbf{Z}_t$ has few properties to recommend it over the AR(4) model for $\mathbf{Z}_t$; it was more complicated, yielded higher residual variances, and except for the chum salmon series, did not produce lower one-step-ahead forecast errors (Table 10.9; Tables F1 through F8 show yearly forecasts by year and species, for comparison to previous results). Residual variances from the vector AR(4) model (Table 10.9) were 68% below RMS from the best univariate or TFN noise model for chum salmon catch (Table 8.12), ≈5% below RMS from the best model for coho and sockeye salmon catches, and 15% *above* RMS from the best model for pink salmon catch. Similarly, mean one-step-ahead forecast errors from the vector AR(4) model (Table 10.9) were 40% (17 percentage points) *above* the best forecasts for chum salmon catch, 23% (3.9 percentage points) below the best forecasts for coho salmon catch, 13% (2.7 percentage points) below the best forecasts for sockeye salmon catch, and 26% (7.2 percentage points) below the best forecasts for pink salmon catch (Table 8.13).

Table 10.8. Parameter estimates and residual statistics for the vector AR(3) model of **first differences** of square root transformed pink, chum, sockeye, and coho salmon catches in southern Southeast Alaska, 1929-1985. $Z_t = [\text{pink}/10^7, \text{chum}/10^6, \text{sock}/10^5, \text{coho}/10^5]^T$.

	Estimates	Standard Errors	Diagonals of Σ
C	$[\cdot \quad \cdot \quad \cdot \quad \cdot]^T$	$[\cdot \quad \cdot \quad \cdot \quad \cdot]^T$	$\begin{bmatrix} 0.082 \\ 0.035 \\ 0.146 \\ 0.205 \end{bmatrix}$
$\underline{\phi}_1$	$\begin{bmatrix} -.76 & \cdot & \cdot & \cdot \\ +.16 & -.76 & \cdot & \cdot \\ \cdot & +.34 & \cdot & \cdot \\ \cdot & \cdot & \cdot & -.57 \end{bmatrix}$	$\begin{bmatrix} .09 & \cdot & \cdot & \cdot \\ .08 & .10 & \cdot & \cdot \\ \cdot & .15 & \cdot & \cdot \\ \cdot & \cdot & \cdot & .10 \end{bmatrix}$	
$\underline{\phi}_2$	$\begin{bmatrix} \cdot & \cdot & \cdot & -.17 \\ +.54 & -.37 & \cdot & \cdot \\ \cdot & \cdot & -.30 & \cdot \\ +.71 & \cdot & \cdot & -.53 \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & .06 \\ .10 & .10 & \cdot & \cdot \\ \cdot & \cdot & .13 & \cdot \\ .17 & \cdot & \cdot & .13 \end{bmatrix}$	
$\underline{\phi}_3$	$\begin{bmatrix} \cdot & \cdot & -.28 & \cdot \\ +.37 & -.46 & -.20 & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & -.42 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & .10 & \cdot \\ .09 & .09 & .07 & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & .15 & \cdot \end{bmatrix}$	

Residual cross-correlations[a] (ρ_{ij}) at lag ℓ

$\ell = 1$	2	3	4	5	6
$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ + & \cdot & \cdot & \cdot \end{bmatrix}$

[a] Indicator symbols +, -, and · denote significant positive, significant negative, or non-significant values of ρ_{ij} (±2 SE), when series j leads series i.

Table 10.9. Residual variances (RMS) and relative forecast errors for vector AR models of square root transformed **pink, chum, sockeye,** and **coho** salmon catches in **southern** (SSE), **northern** (NSE), and **Southeast** (SE) **Alaska.** Forecast errors are the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE).

	Species:	Model type	RMS	Forecast Error: Median	Forecast Error: Mean	Forecast Error: MPE
SSE AK	Pink:	AR(4), Z_t	0.0697	17.2	21.0	-19.9
		AR(3), ∇Z_t	0.0821	14.0	26.9	-26.9
	Chum:	AR(4), Z_t	0.0317	31.3	58.3	50.7
		AR(3), ∇Z_t	0.0354	20.2	27.5	-19.4
	Sock:	AR(4), Z_t	0.1391	16.3	17.9	-3.7
		AR(3), ∇Z_t	0.1460	26.8	21.9	-5.4
	Coho:	AR(4), Z_t	0.1857	5.0	12.8	5.5
		AR(3), ∇Z_t	0.2052	20.2	20.6	-16.0

	Species:	Model type	RMS	Median	Mean	MPE
NSE AK	Pink:	AR(4), Z_t	0.0686	42.6	46.6	-27.1
		AR(3), ∇Z_t	0.0711	50.5	51.3	-31.1
	Chum:	AR(4), Z_t	0.0228	25.1	44.5	45.5
		AR(3), ∇Z_t	0.0389	12.4	27.9	-0.2
	Sock:	AR(4), Z_t	0.0715	19.0	17.6	0.0
		AR(3), ∇Z_t	0.1317	3.3	12.5	-12.1
	Coho:	AR(4), Z_t	0.2073	27.6	27.5	-21.9
		AR(3), ∇Z_t	0.2717	11.7	18.8	-18.8

- continued -

Table 10.9. (p.2 of 2).

	Species:	Model type	RMS	Forecast Error: Median	Mean	MPE
	Pink:	AR(4), Z_t	0.0905	32.0	29.1	-29.1
		AR(3), ∇Z_t	0.1195	41.6	31.7	-31.7
S E	Chum:	AR(4), Z_t	0.0637	29.3	32.8	7.9
		AR(3), ∇Z_t	0.0711	16.5	26.0	-14.6
A K	Sock:	AR(4), Z_t	0.0210	12.7	18.3	-13.2
		AR(3), ∇Z_t	0.0231	19.4	18.5	-10.8
	Coho:	AR(4), Z_t	0.0295	24.9	22.9	-22.9
		AR(3), ∇Z_t	0.0318	18.7	17.7	-17.7

Northern Southeast Alaska

The unrestricted AR(4) model was fit to $\mathbf{Z}_t$ for northern Southeast Alaska, and only three residual cross-correlations $\rho_{ij}(\mathcal{L})$ were significant to lag 6 (1 at $\mathcal{L}$=3 and 2 at $\mathcal{L}$=6). Thus, parameters for moving average terms were not added to the model, and three additional estimations yielded a stationary model with 16 parameters (Table 10.10).

Only 1 of 96 cross-correlations computed between residuals from the final estimation was significant at 2 SE (Table 10.10) suggesting an adequate fit to the data. In contrast to results for southern Southeast Alaska, a feedback relationship between pink and coho salmon catch was not present, while the component relationships for chum and sockeye salmon are not intuitive and complex. The AR(4) model relates pink (Pk), chum (Cm), sockeye (So), and coho (Co) salmon catches:

$$Pk_t = c + \alpha_1 Pk_{t-1} + \alpha_2 Pk_{t-2} + a_{1t} \tag{10.9}$$

$$Cm_t = c + \beta_2 Pk_{t-2} - \beta_2 So_{t-2} + \beta_2 Co_{t-2} + \beta_3 Pk_{t-3} + \beta_3 Co_{t-3} + \beta_4 Cm_{t-4} + a_{2t} \tag{10.10}$$

$$So_t = c + \gamma_1 Pk_{t-1} + \gamma_1 So_{t-1} + \gamma_2 Pk_{t-2} + \gamma_2 Cm_{t-2} - \gamma_2 So_{t-2} - \gamma_4 So_{t-4} + a_{3t} \tag{10.11}$$

$$Co_t = c + \delta_1 Co_{t-1} - \delta_3 Cm_{t-3} + a_{4t} \tag{10.12}$$

where c, and α_x, β_x, γ_x, and δ_x signify the appropriate parameters in Table 10.10. The residual correlation matrix

$$\begin{bmatrix} 1.00 & & & \\ 0.12 & 1.00 & & \\ 0.33 & 0.23 & 1.00 & \\ 0.32 & 0.17 & 0.22 & 1.00 \end{bmatrix}$$

indicates weak to moderate contemporaneous relations between the series.

Some elements of the fitted equations (10.9-10.12) are, again, similar to elements of the ARMA and TFN models in previous analyses: pink salmon catch is related to itself at t-1 and t-2; chum salmon catch is related to itself at t-4; sockeye salmon catch is related to itself at lag 1, and; coho salmon catch is related to itself at t-1.

The AR(3) model for $\nabla\mathbf{Z}_t$ (10.2) was fit to the data in five estimation steps. The result was a stationary model with 9 parameters, and two significant residual cross-correlations to lag 6 (Table 10.11). The model contains no feedback between variables:

Table 10.10. Parameter estimates and residual statistics for the vector AR(4) model of square root transformed pink, chum, sockeye, and coho salmon catches in northern Southeast Alaska, 1928-1985. $Z_t = [\text{pink}/10^7, \text{chum}/10^6, \text{sock}/10^5, \text{coho}/10^5]^T$.

	Estimates	Standard Errors	Diagonals of Σ
C	$[+0.31\ \ -0.44\ \ +0.85\ \ +2.33]^T$	$[0.10\ \ 0.16\ \ 0.18\ \ 0.38]^T$	$\begin{bmatrix} 0.069 \\ 0.023 \\ 0.072 \\ 0.207 \end{bmatrix}$
$\underline{\phi}_1$	$\begin{bmatrix} +.26 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ +.40 & \cdot & +.49 & \cdot \\ \cdot & \cdot & \cdot & +.28 \end{bmatrix}$	$\begin{bmatrix} .13 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ .14 & \cdot & .10 & \cdot \\ \cdot & \cdot & \cdot & .12 \end{bmatrix}$	
$\underline{\phi}_2$	$\begin{bmatrix} +.31 & \cdot & \cdot & \cdot \\ +.64 & \cdot & -.16 & +.20 \\ +.57 & +.38 & -.21 & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} .12 & \cdot & \cdot & \cdot \\ .08 & \cdot & .05 & .04 \\ .15 & .11 & .10 & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	
$\underline{\phi}_3$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ .50 & \cdot & \cdot & .13 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & -.50 & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ .08 & \cdot & \cdot & .04 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & .16 & \cdot & \cdot \end{bmatrix}$	
$\underline{\phi}_4$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & +.29 & \cdot & \cdot \\ \cdot & \cdot & -.25 & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & .07 & \cdot & \cdot \\ \cdot & \cdot & .08 & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	

Residual cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$\mathcal{L} = 1$	2	3	4	5	6
$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$

[a] Indicator symbols +, -, and • denote significant positive, significant negative, or non-significant values of ρ_{ij} (± 2 SE), when series j leads series i.

Table 10.11. Parameter estimates and residual statistics for the vector AR(3) model of first differences of square root transformed pink, chum, sockeye, and coho salmon catches in northern Southeast Alaska, 1928-1985. $\mathbf{Z}_t = [\text{pink}/10^7, \text{chum}/10^6, \text{sock}/10^5, \text{coho}/10^5]^T$.

	Estimates	Standard Errors	Diagonals of Σ
C	$[\,\cdot\ \ \cdot\ \ \cdot\ \ \cdot\,]^T$	$[\,\cdot\ \ \cdot\ \ \cdot\ \ \cdot\,]^T$	$\begin{bmatrix} 0.071 \\ 0.039 \\ 0.132 \\ 0.272 \end{bmatrix}$
$\underline{\phi}_1$	$\begin{bmatrix} -.74 & \cdot & \cdot & \cdot \\ \cdot & -.29 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & -.48 \end{bmatrix}$	$\begin{bmatrix} .12 & \cdot & \cdot & \cdot \\ \cdot & .10 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & .10 \end{bmatrix}$	
$\underline{\phi}_2$	$\begin{bmatrix} -.43 & \cdot & \cdot & \cdot \\ +.69 & \cdot & \cdot & +.11 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} .12 & \cdot & \cdot & \cdot \\ .10 & \cdot & \cdot & .05 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	
$\underline{\phi}_3$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ +.75 & -.18 & \cdot & \cdot \\ \cdot & +.29 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ .10 & .09 & \cdot & \cdot \\ \cdot & .15 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	

Residual cross-correlations[a] (ρ_{ij}) at lag ℓ

$\ell = 1$	2	3	4	5	6
$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & + & \cdot & \cdot \end{bmatrix}$

[a] Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values of ρ_{ij} (± 2 SE), when series j leads series i.

$$\nabla Pk_t = -\alpha_1 \nabla Pk_{t-1} - \alpha_2 \nabla Pk_{t-2} + a_{1t} \tag{10.13}$$

$$\nabla Cm_t = -\beta_1 \nabla Cm_{t-1} + \beta_2 \nabla Pk_{t-2} + \beta_2 \nabla Co_{t-2} + \beta_3 \nabla Pk_{t-3} - \beta_3 \nabla Cm_{t-3} + a_{2t} \tag{10.14}$$

$$\nabla So_t = \alpha_3 \nabla Cm_{t-3} + a_{3t} \tag{10.15}$$

$$\nabla Co_t = -\delta_1 \nabla Co_{t-1} + a_{4t} \tag{10.16}$$

and has a residual correlation matrix

$$\begin{bmatrix} 1.00 & & & \\ -0.02 & 1.00 & & \\ 0.25 & 0.21 & 1.00 & \\ 0.46 & 0.17 & 0.20 & 1.00 \end{bmatrix}$$

which is similar to that from the AR(4) model. The equations for pink (10.13) and coho (10.16) salmon catches in this model are somewhat familiar, while the equation for sockeye salmon catch (10.15) has no obvious biological interpretation.

Although the AR(3) model for ∇Z_t produced higher residual variances than the AR(4) model for Z_t, the model for ∇Z_t contained 7 less parameters, and except for the pink salmon series, yielded lower one-step-ahead forecast errors (Table 10.9; Tables F1 through F8). Residual variances from the VARMA(3,1,0) model (Table 10.9) were 81% *above* RMS from the best univariate or TFN noise model (Table 8.12) for coho salmon catch, 23% *above* RMS from the best model for pink salmon catch, 1% *above* RMS from the best model for sockeye salmon catch, and 28% below RMS from the best model for chum salmon catch. Similarly, mean one-step-ahead forecast errors from the VARMA(3,1,0) model (Table 10.9) were about the same as the best forecasts for coho salmon catch, 44% (16 percentage points) *above* the best forecasts for pink salmon catch, 20% (3.1 percentage points) below the best forecasts for sockeye salmon catch, and 29% (6.3 percentage points) *above* the best forecasts for chum salmon catch (Table 8.13).

Southeast Alaska

The AR(4) model was fit to Z_t for Southeast Alaska, and since only one residual cross-correlation (at $\mathcal{L}$=5) was significant to $\mathcal{L}$=6, moving average terms were not added to the model. Four additional estimations were made to arrive at a stationary model with 18 parameters (Table 10.12).

Two of 96 cross-correlations computed between residuals from the final estimation were significant at 2 SE (Table 10.12) indicating an adequate model for Z_t.

Table 10.12. Parameter estimates and residual statistics for the vector AR(4) model of square root transformed pink, chum, sockeye, and coho salmon catches in Southeast Alaska, 1918-1985. $Z_t = [\text{pink}/10^7, \text{chum}/10^6, \text{sock}/10^6, \text{coho}/10^6]^T$.

	Estimates	Standard Errors	Diagonals of Σ
C	$[+0.05\ \ -0.35\ \ +0.19\ \ +0.63]^T$	$[0.25\ \ 0.21\ \ 0.08\ \ 0.14]^T$	$\begin{bmatrix} 0.091 \\ 0.064 \\ 0.021 \\ 0.029 \end{bmatrix}$
$\underline{\phi}_1$	$\begin{bmatrix} \cdot & \cdot & \cdot & +.55 \\ \cdot & +.33 & \cdot & \cdot \\ \cdot & \cdot & +.79 & \cdot \\ \cdot & \cdot & \cdot & +.29 \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & .17 \\ \cdot & .08 & \cdot & \cdot \\ \cdot & \cdot & .11 & \cdot \\ \cdot & \cdot & \cdot & .10 \end{bmatrix}$	
$\underline{\phi}_2$	$\begin{bmatrix} +.47 & \cdot & \cdot & -.43 \\ +.70 & \cdot & \cdot & \cdot \\ +.11 & \cdot & -.45 & \cdot \\ +.17 & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} .11 & \cdot & \cdot & .18 \\ .09 & \cdot & \cdot & \cdot \\ .05 & \cdot & .14 & \cdot \\ .06 & \cdot & \cdot & \cdot \end{bmatrix}$	
$\underline{\phi}_3$	$\begin{bmatrix} \cdot & -.17 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & +.35 & \cdot \\ \cdot & \cdot & -.20 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & .06 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & .10 & \cdot \\ \cdot & \cdot & .09 & \cdot \end{bmatrix}$	
$\underline{\phi}_4$	$\begin{bmatrix} \cdot & \cdot & +.75 & \cdot \\ -.38 & +.34 & \cdot & +.40 \\ \cdot & \cdot & \cdot & \cdot \\ +.17 & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & .14 & \cdot \\ .12 & .07 & \cdot & .20 \\ \cdot & \cdot & \cdot & \cdot \\ .05 & \cdot & \cdot & \cdot \end{bmatrix}$	

Residual cross-correlations[a] (ρ_{ij}) at lag ℓ

$\ell = 1$	2	3	4	5	6
$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix}$

[a] Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values of ρ_{ij} (± 2 SE), when series j leads series i.

The AR(4) model relates pink (Pk), chum (Cm), sockeye (So), and coho (Co) salmon catches in Southeast Alaska as a very complicated system:

$$Pk_t = c + \alpha_1 Co_{t-1} + \alpha_2 Pk_{t-2} - \alpha_2 Co_{t-2} - \alpha_3 Cm_{t-3} + \alpha_4 So_{t-4} + a_{1t} \quad (10.17)$$

$$Cm_t = c + \beta_1 Cm_{t-1} + \beta_2 Pk_{t-2} - \beta_4 Pk_{t-4} + \beta_4 Cm_{t-4} + \beta_4 Co_{t-4} + a_{2t} \quad (10.18)$$

$$So_t = c + \gamma_1 So_{t-1} + \gamma_2 Pk_{t-2} - \gamma_2 So_{t-2} + \gamma_3 So_{t-3} + a_{3t} \quad (10.19)$$

$$Co_t = c + \delta_1 Co_{t-1} + \delta_2 Pk_{t-2} - \delta_3 So_{t-3} + \delta_4 Pk_{t-4} + a_{4t} \quad (10.20)$$

where c, and α_x, β_x, γ_x, and δ_x relate to the parameters in Table 10.12. The component equations indicate feedback between catches of pink and coho, and pink and sockeye, salmon as found in southern Southeast Alaska, and between pink and chum salmon catches. Some of the complexity reflected in equations 10.17 to 10.20 may result because these series integrate features of the southern and northern Southeast Alaska data.

The AR(3) model for ∇Z_t (10.2) was fit to the data in three estimation steps. The result was a stationary model with 13 parameters, and two significant residual cross-correlations to lag 6 (Table 10.13). The model contains feedback between series which is similar to, and simpler than, feedback in the model for southern Southeast Alaska:

$$\nabla Pk_t = -\alpha_1 \nabla Pk_{t-1} - \alpha_2 \nabla Co_{t-2} - \alpha_3 \nabla So_{t-3} + a_{1t} \quad (10.21)$$

$$\nabla Cm_t = -\beta_1 \nabla Cm_{t-1} + \beta_2 \nabla Pk_{t-2} - \beta_2 \nabla Cm_{t-2} + \beta_3 \nabla Pk_{t-3} - \beta_3 \nabla Cm_{t-3} + a_{2t} \quad (10.22)$$

$$\nabla So_t = -\alpha_2 \nabla So_{t-2} + a_{3t} \quad (10.23)$$

$$\nabla Co_t = -\delta_1 \nabla Co_{t-1} + \delta_2 \nabla Pk_{t-2} - \delta_2 \nabla Co_{t-2} - \delta_3 \nabla So_{t-3} + a_{4t} \quad (10.24)$$

The AR(3) model for ∇Z_t yielded higher residual variances than the AR(4) model for Z_t (Table 10.9). However, the model for ∇Z_t contained five less parameters and forecast the catches of chum, coho, and sockeye about as well or better than the AR(4) model (Table 10.9; Tables F1 through F8). Residual variances from the VARMA(3,1,0) model (Table 10.9) were 28% *above* RMS from the best univariate or TFN noise model (Table 8.12) for sockeye salmon catch, 22% *above* RMS from the best model for coho salmon catch, 6% *above* RMS from the best model for pink salmon catch, and 38% below RMS from the best model for chum salmon catch. Similarly, mean one-step-ahead forecast errors from the VARMA(3,1,0) model (Table 10.9) were 45% (5.7 percentage

Table 10.13. Parameter estimates and residual statistics for the vector AR(3) model of first differences of square root transformed pink, chum, sockeye, and coho salmon catches in Southeast Alaska, 1918-1985. Z_t = [pink/10^7, chum/10^6, sock/10^6, coho/10^6]^T.

	Estimates	Standard Errors	Diagonals of Σ
C	$[\cdot \quad \cdot \quad \cdot \quad \cdot]^T$	$[\cdot \quad \cdot \quad \cdot \quad \cdot]^T$	$\begin{bmatrix} 0.119 \\ 0.071 \\ 0.023 \\ 0.032 \end{bmatrix}$
Φ_1	$\begin{bmatrix} -.65 & \cdot & \cdot & \cdot \\ \cdot & -.52 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & -.62 \end{bmatrix}$	$\begin{bmatrix} .08 & \cdot & \cdot & \cdot \\ \cdot & .08 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & .10 \end{bmatrix}$	
Φ_2	$\begin{bmatrix} \cdot & \cdot & \cdot & -.60 \\ +.53 & -.27 & \cdot & \cdot \\ \cdot & \cdot & -.30 & \cdot \\ +.18 & \cdot & \cdot & -.51 \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot & .18 \\ .09 & .08 & \cdot & \cdot \\ \cdot & \cdot & .11 & \cdot \\ .05 & \cdot & \cdot & .12 \end{bmatrix}$	
Φ_3	$\begin{bmatrix} \cdot & \cdot & -.65 & \cdot \\ +.48 & -.44 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & -.30 & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & .24 & \cdot \\ .10 & .08 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & .13 & \cdot \end{bmatrix}$	

Residual cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$$\begin{array}{cccccc} \mathcal{L}=1 & 2 & 3 & 4 & 5 & 6 \\ \begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} & \begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} & \begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} & \begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} & \begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} & \begin{bmatrix} \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & + & \cdot \\ \cdot & \cdot & \cdot & \cdot \end{bmatrix} \end{array}$$

[a] Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values of ρ_{ij} (± 2 SE), when series j leads series i.

points) *above* the best forecasts for sockeye salmon catch, 8% (1.3 percentage points) *above* the best forecasts for coho salmon catch, 36% (8.4 percentage points) *above* the best forecasts for pink salmon catch, and 18% (5.9 percentage points) below the best forecasts for chum salmon catch (Table 8.13).

10.3 Approach to Modeling Catch and Environmental Data

Catches of pink, sockeye, and coho salmon in southern Southeast and Southeast Alaska contain evidence of feedback which is characterized in the VARMA models for both $\mathbf{Z}_t$ and $\nabla\mathbf{Z}_t$ (Section 10.2). This statistical relationship was of special practical significance, since the feedback between catches, along with information on environment, might jointly improve forecasts of pink salmon catch in southern Southeast Alaska. Since forecasting this series is of special economic significance in Southeast Alaska (Chapter 1), the following analysis focused on these data and statistical relationships. As a result, the series of chum salmon catches were not used in the analysis.

The data vector $\mathbf{Z}_t = [\text{pink,sock,coho},e_1,..,e_n]^T$, e_j being environmental series j, was used to build a joint model for southern Southeast Alaska. To make catch and environmental series equal in length, mean values were appended to the beginning of short environmental series, as discussed in Section 7.4 and Chapter 8. In constructing the VARMA models I assumed catch does not affect the physical environment, and that the environmental series could be modeled and forecast by their own mean values. Thus, coefficient matrices in the model are block rectangular (Chapter 9). The first assumption is intuitively true. Autocorrelations for the environmental series (Chapter 5) tend to be weak and/or occur at high lags, so the second assumption is reasonable, simplifies the model, and significantly reduces computations.

Variables identified in the univariate (TFN model) analysis (Tables 8.1, 8.5, 8.8) were considered for this analysis. Thus, mean winter air temperatures (SSEwint), inland SST (SSEsst), and alongshore wind speed (Nwind) were in models for $\mathbf{Z}_t$. The variable for low winter air temperatures (SSEcold) which was included in the model for sockeye salmon catch (Table 8.8) was omitted because the closely related (r=.73) series SSEwint was preferred in models for pink and coho salmon catch (Tables 8.1 and 8.5). Because upwelling (SEupw) was favored over Nwind in the TFN model for first differences in pink salmon catch (Table 8.1), Nwind and SEupw were alternately considered in VARMA models for $\nabla\mathbf{Z}_t$. Preliminary models which included discharges of fresh water into the Gulf of Alaska (SSEdis) and SST data for 55^0N (SST55s) suggested the important conclusions of the analysis, especially regarding pink salmon, were unlikely to be different had these variables been included in $\mathbf{Z}_t$.

The identification procedures outlined in Chapter 9 were adapted to select a tentative model for $\mathbf{Z}_t$. Given the two assumptions for the model (above), only cross-correlation and partial autoregression coefficients germane to the three catch series (the 3×3 sub-matrices of $\underline{\rho}(\mathcal{L})$ and $\underline{\mathcal{P}}(\mathcal{L})$ defined by i,j = 1 to 3) were used to form identifications. Application of the statistic $M(\mathcal{L})$ (9.7), which is computed from residuals of all series in $\mathbf{Z}_t$, is less obvious. Thus, a modified $M(\mathcal{L})$ statistic $M(\mathcal{L})^*$ with $S(\mathcal{L})$ being the determinant of the matrix of residual sums of squares and cross-products for the *catch series only*, and k=3 (degrees of freedom), was computed for comparison to $M(\mathcal{L})$. Assuming k=3 leads to a critical value for $M(\mathcal{L})^* \approx 17$ ($\chi^2_{9,\ 0.05}$). Although the distribution of $M(\mathcal{L})^*$ is unknown, comparison of both statistics by lag $\mathcal{L}$ was used to suggest if $M(\mathcal{L})$ could be greatly misleading. Cross-correlations for the analysis were computed to $\mathcal{L}$=6. Other aspects of the modeling were as in Section 10.1, except that 2 (not 1.5) SE was initially used to select parameters in seeking a parsimonious model, and covariances between the residual series for fish and environment (the off-diagonal blocks of $\underline{\Sigma}$) were set to 0 when fitting tentative models prior to the final estimations.

10.4 Models for Salmon Catch and Environment in Southern Southeast Alaska

Persistent cross-correlations between the series suggested low-order moving average models were not appropriate for modeling these series (Table 10.14). $M(\mathcal{L})$ statistics were significant at lags 1 and 2 (since $\chi^2_{36,\ 0.05} = 52.6$). However, assuming a critical value of 17 for $M(\mathcal{L})^*$ leads to consideration of an AR(4) model for $\mathbf{Z}_t$ (Table 10.14). Vector AR(2) and AR(4) models were thus fit to the series. Because environmental data were not significant (±2 SE) in the final AR(4) model, results for the vector AR(2) model

$$(\underline{I} - \underline{\phi}_1 B - \underline{\phi}_2 B^2)\ \mathbf{Z}_t = \mathbf{C} + \mathbf{a}_t \qquad (10.25)$$

are presented. The AR(4) model for $\mathbf{Z}_t$ yielded a result similar to equations (10.3), (10.5), and (10.6).

Two residual cross-correlations from fitting the unrestricted AR(2) model were significant (±2 SE) at lag 2. Parameter matrices for moving average terms were not added to the model and 3 additional estimations were made to arrive with a model having 8 parameters (excluding the constants in **C**) significant at 2 SE (Table 10.15).

Table 10.14. Cross-correlation, partial autoregression, and other statistics for modeling southern Southeast Alaska salmon catches 1929-1985, and environmental data. Z_t = [$\sqrt{pink/10^7}$, $\sqrt{sock/10^5}$, $\sqrt{coho/10^5}$, SSEwint, SSEsst, Nwind]^T.

Cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$$\begin{array}{cccccc} \mathcal{L}=1 & 2 & 3 & 4 & 5 & 6 \\ \begin{bmatrix} + & + & + \\ + & + & + \\ + & + & + \end{bmatrix} & \begin{bmatrix} + & + & + \\ + & + & \cdot \\ + & + & + \end{bmatrix} & \begin{bmatrix} + & + & + \\ + & + & \cdot \\ + & + & + \end{bmatrix} & \begin{bmatrix} + & + & + \\ + & + & \cdot \\ + & + & + \end{bmatrix} & \begin{bmatrix} + & + & \cdot \\ + & + & \cdot \\ + & + & + \end{bmatrix} & \begin{bmatrix} + & + & \cdot \\ \cdot & \cdot & \cdot \\ + & + & + \end{bmatrix} \end{array}$$

Partial autoregression coefficients[a] ($\wp_{ij}$), M, M*, and residual variances (Σ), at lag $\mathcal{L}$

$\mathcal{L}$	$\wp_{ij}$	M	M*	Σ (i=j=1,2,3)
1	$\begin{bmatrix} \cdot & + & \cdot \\ + & + & \cdot \\ \cdot & \cdot & + \end{bmatrix}$	105.	81.6	0.114 0.123 0.285
2	$\begin{bmatrix} + & \cdot & - \\ + & \cdot & \cdot \\ + & \cdot & \cdot \end{bmatrix}$	53.3	37.0	0.0632 0.101 0.173
3	$\begin{bmatrix} \cdot & + & + \\ + & \cdot & - \\ \cdot & \cdot & + \end{bmatrix}$	44.2	32.7	0.0462 0.0697 0.135
4	$\begin{bmatrix} \cdot & + & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & + & \cdot \end{bmatrix}$	32.4	25.5	0.0365 0.0612 0.0900
5	$\begin{bmatrix} \cdot & \cdot & \cdot \\ + & + & - \\ \cdot & \cdot & \cdot \end{bmatrix}$	32.5	15.3	0.0330 0.0455 0.0729

[a] Indicator symbols +, -, and · denote significant positive, significant negative, or non-significant values (ρ_{ij} or $\wp_{ij}$, ±2 SE), when series j leads series i; for series i,j = 1 to 3.

Table 10.15. Parameter estimates and residual statistics for the vector AR(2) model of **southern Southeast Alaska** pink, sockeye, and coho salmon catch, 1929-1985, and environmental data. $Z_t = [\sqrt{pink}/10^7, \sqrt{sock}/10^5, \sqrt{coho}/10^5, SSEwint, SSEsst, Nwind]^T$.

	Estimates	Standard Errors
C	$[-0.40\ \ +0.60\ \ -0.76\ \ +35.3\ \ +51.0\ \ -1.97]^T$	$[0.43\ \ 0.20\ \ 0.73\ \ 0.42\ \ 0.18\ \ 0.12]^T$

$$\underline{\Phi}_1 \quad \begin{bmatrix} \cdot & \cdot & \cdot & +.035 & \cdot & +.095 \\ \cdot & +.736 & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & +.308 & +.045 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \qquad \begin{bmatrix} \cdot & \cdot & \cdot & .011 & \cdot & .036 \\ \cdot & .088 & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & .080 & .019 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

$$\underline{\Phi}_2 \quad \begin{bmatrix} +.923 & \cdot & -.200 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ +.959 & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \qquad \begin{bmatrix} .135 & \cdot & .065 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ .171 & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

Diagonals of $\underline{\Sigma}$ = [0.077 0.156 0.225 9.680 1.789 0.837]

Residual cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$ (first three rows only)

$$\begin{array}{ccccc} \mathcal{L} = 1 & 2 & 3 & 4 & 5 \\ \begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \end{bmatrix} & \begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \end{bmatrix} & \begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&-&\cdot&\cdot&\cdot&\cdot \end{bmatrix} & \begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&+&\cdot \end{bmatrix} & \begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \end{bmatrix} \end{array}$$

[a] Indicator symbols +, -, and • denote significant positive, significant negative, or non-significant values of ρ_{ij} (±2 SE), when series j leads series i.

No cross-correlations between residual catch and environmental series from the final estimation were significant (±2 SE) to $\mathcal{L}$=2, suggesting an adequate fit to the data. Also, only 2 residual cross-correlations were significant to lag 5 (Table 10.15), and the model is stationary. Feedback between pink (Pk) and coho (Co) salmon catch remained in the model while sockeye (So) salmon catches could be ignored. Winter air temperature (T) and alongshore wind speed near Seward (W) also remained in the model, which in equation form is:

$$Pk_t = c + \alpha_1 T_{t-1} + \alpha_1 W_{t-1} + \alpha_2 Pk_{t-2} - \alpha_2 Co_{t-2} + a_{1t} \tag{10.26}$$

$$So_t = c + \gamma_1 So_{t-1} + a_{2t} \tag{10.27}$$

$$Co_t = c + \delta_1 Co_{t-1} + \delta_1 T_{t-1} + \delta_2 Pk_{t-2} + a_{3t} \tag{10.28}$$

where c, and α_x, γ_x, and δ_x are, respectively, appropriate elements of **C** and the $\underline{\phi}_x$ matrices in Table 10.15. The residual correlations

$$\begin{bmatrix} 1.00 & & \\ 0.25 & 1.00 & \\ 0.57 & 0.09 & 1.00 \end{bmatrix}$$

are essentially the same as before adding environmental data to the model.

Equations 10.26 and 10.28 remind us that pink and coho salmon catches are strongly related to themselves. However, we now infer that pink salmon catch is nearly non-stationary (ϕ_2=0.92). Sockeye salmon catch presumably drops from the model for pink and coho salmon catch (relative to 10.3-10.6) because temperature and wind speed better explain the variability. Other parameters would probably enter the model for sockeye salmon catch if $\mathcal{L}$ was higher than 2.

Models for first differences of the catch series was also constructed, since the series could be nonstationary. In the first analysis, SSEwint, SSEsst, and Nwind were included in $\mathbf{Z}_t$. Cross-correlations between the transformed catches could be "cut-off" at lag 2, indicating a MA(2) model for the data (Table 10.16). M($\mathcal{L}$) statistics were significant only through lag 1, but M($\mathcal{L}$)* statistics were significant through lag 2, given a critical value of 17 (Table 10.16). Residual variances for the differenced pink and coho salmon catches again drop quickly through lag 2, while residual variances for sockeye salmon drop slowly through lag 5. A good identification for a model is not

Table 10.16. Cross-correlation, partial autoregression, and other statistics for modeling first differences of southern Southeast Alaska salmon catches 1929-1985, and environmental data set A. $Z_t = [\sqrt{pink}/10^7, \sqrt{sock}/10^5, \sqrt{coho}/10^5, SSEwint, SSEsst, Nwind]^T$.

Cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$

$\mathcal{L} = 1$	2	3	4	5	6
$\begin{bmatrix} - & \cdot & - \\ \cdot & \cdot & \cdot \\ - & \cdot & - \end{bmatrix}$	$\begin{bmatrix} + & \cdot & \cdot \\ \cdot & - & \cdot \\ + & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ - & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ + & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$

Partial autoregression coefficients[a] ($\wp_{ij}$), M, M^*, and residual variances (Σ), at lag $\mathcal{L}$

$\mathcal{L}$	$\wp_{ij}$	M	M^*	Σ (i=j=1,2,3)
1	$\begin{bmatrix} - & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ - & + & - \end{bmatrix}$	76.5	63.7	0.0719 0.160 0.215
2	$\begin{bmatrix} \cdot & - & - \\ \cdot & - & \cdot \\ + & \cdot & - \end{bmatrix}$	43.0	31.0	0.0492 0.136 0.161
3	$\begin{bmatrix} \cdot & \cdot & \cdot \\ + & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$	29.9	15.2	0.0429 0.115 0.142
4	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & - & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$	33.1	30.4	0.0333 0.0861 0.104
5	$\begin{bmatrix} \cdot & \cdot & \cdot \\ + & + & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$	39.5	23.9	0.0312 0.0483 0.0872

a Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values (ρ_{ij} or $\wp_{ij}$, ± 2 SE), when series j leads series i; for series i,j = 1 to 3.

apparent. Much of the variation in the pink and coho salmon series to lag 5 was explained with regressions to lag 2, so the vector AR(2) model

$$(\underline{I} - \underline{\phi}_1 B - \underline{\phi}_2 B^2)\,(\underline{I} - B)\,\mathbf{Z}_t = \mathbf{C} + \mathbf{a}_t \qquad (10.29)$$

was tentatively fit to the data.

No residual cross-correlations from fitting the unrestricted AR model were significant (±2 SE) to lag 2 so moving average parameters were not added to the model. Three additional estimations were made to arrive with a model having 13 parameters (excluding constants in C) significant at 2 SE (Table 10.17).

No cross-correlation between residual catch and environmental series from the final estimation was significant (±2 SE) to $\mathcal{L}$=2, suggesting an adequate fit to the data. Also, only 1 residual cross-correlation was significant to lag 5 (Table 10.17), and the model was stationary. Feedback between pink (Pk) and coho (Co) salmon catch remained in the model, and sockeye (So) salmon, winter air temperature (T), alongshore wind speed near Seward (W), and inland SST (I) also remained in the model:

$$\nabla Pk_t = c - \alpha_1 \nabla Pk_{t-1} + \alpha_1 T_{t-1} + \alpha_1 W_{t-1}$$

$$+ \alpha_2 \nabla Pk_{t-2} - \alpha_2 \nabla So_{t-2} - \alpha_2 \nabla Co_{t-2} - \alpha_2 I_{t-2} - \alpha_2 W_{t-2} + a_{1t} \qquad (10.30)$$

$$\nabla So_t = c - \gamma_2 \nabla So_{t-2} + a_{2t} \qquad (10.31)$$

$$\nabla Co_t = c - \delta_1 \nabla Co_{t-1} + \delta_1 T_{t-1} + \delta_2 \nabla Pk_{t-2} - \delta_2 \nabla Co_{t-2} + a_{3t} \qquad (10.32)$$

where c, and α_x, γ_x, and δ_x are, respectively, appropriate elements of **C** and the $\underline{\phi}_x$ matrices in Table 10.17.

The second analysis for the differenced series of catches used the variable SEupw instead of Nwind. Cross-correlations between the transformed catches are largely "cut-off" at lag 2, suggesting a MA(2) model for the data (Table 10.18). However, fitting this model leaves four residual correlations at lag 1, indicating the MA model is not appropriate. M($\mathcal{L}$) statistics were significant only through lag 1, but M($\mathcal{L}$)* statistics were significant at all lags (1-5), given a critical value of 17 (Table 10.18). In contrast to the analysis using Nwind, residual variance for the pink salmon series does not drop steeply at lag 2. A good identification is again not apparent. Fitting a vector AR(1) model to the series leaves four residual correlations at lag 2. The vector AR(2,1,0) model was

Table 10.17. Parameter estimates and residual statistics for the vector AR(2) model of first differences of southern Southeast Alaska pink, sockeye, and coho salmon catch, 1929-1985, and environmental data set A. $\mathbf{Z}_t = [\sqrt{\text{pink}/10^7}, \sqrt{\text{sock}/10^5}, \sqrt{\text{coho}/10^5}, \text{SSEwint}, \text{SSEsst}, \text{Nwind}]^T$.

	Estimates	Standard Errors
C	$[+1.26\ \ +0.01\ \ -1.62\ \ +35.2\ \ +51.0\ \ -1.97]^T$	$[1.05\ \ 0.05\ \ 0.71\ \ 0.41\ \ 0.18\ \ 0.13]^T$
$\underline{\Phi}_1$	$\begin{bmatrix} -0.652 & \cdot & \cdot & +.028 & \cdot & +.129 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & -.534 & +.046 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} .094 & \cdot & \cdot & .010 & \cdot & .032 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & .103 & .020 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$
$\underline{\Phi}_2$	$\begin{bmatrix} +.325 & -.165 & -.289 & \cdot & -.043 & -.111 \\ \cdot & -.345 & \cdot & \cdot & \cdot & \cdot \\ +.736 & \cdot & -.489 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} .132 & .067 & .071 & \cdot & .020 & .035 \\ \cdot & .130 & \cdot & \cdot & \cdot & \cdot \\ .210 & \cdot & .136 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$

Diagonals of $\underline{\Sigma}$ = $[0.056\ \ 0.156\ \ 0.222\ \ 9.139\ \ 1.760\ \ 0.852]$

Residual cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$ (first three rows only)

$\mathcal{L} = $ 1, 2, 3, 4, 5

$$\begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & - & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

[a] Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values of ρ_{ij} (±2 SE), when series j leads series i.

Table 10.18. Cross-correlation, partial autoregression, and other statistics for modeling first differences of southern Southeast Alaska salmon catches 1929-1985, and environmental data set B. Z_t = [$\sqrt{pink/10^7}$, $\sqrt{sock/10^5}$, $\sqrt{coho/10^5}$, SSEwint, SSEsst, SEupw]^T.

Cross-correlations[a] (ρ_{ij}) at lag ℓ

ℓ = 1	2	3	4	5	6
$\begin{bmatrix} - & \cdot & - \\ \cdot & \cdot & \cdot \\ - & \cdot & - \end{bmatrix}$	$\begin{bmatrix} + & \cdot & \cdot \\ \cdot & - & \cdot \\ + & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ - & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ + & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$

Partial autoregression coefficients[a] ($\wp_{ij}$), M, M*, and residual variances (Σ), at lag ℓ

ℓ	$\wp_{ij}$	M	M*	Σ (i=j=1,2,3)
1	$\begin{bmatrix} - & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ - & + & - \end{bmatrix}$	71.1	62.4	0.0729 0.164 0.206
2	$\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & - & \cdot \\ + & \cdot & - \end{bmatrix}$	31.6	23.1	0.0602 0.136 0.166
3	$\begin{bmatrix} \cdot & - & - \\ + & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$	30.1	18.7	0.0494 0.117 0.144
4	$\begin{bmatrix} \cdot & \cdot & + \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$	31.4	17.6	0.0425 0.107 0.118
5	$\begin{bmatrix} \cdot & \cdot & \cdot \\ + & + & - \\ \cdot & \cdot & \cdot \end{bmatrix}$	40.9	35.5	0.0412 0.0454 0.0994

a Indicator symbols +, -, and $\cdot$ denote significant positive, significant negative, or non-significant values (ρ_{ij} or $\wp_{ij}$, ±2 SE), when series j leads series i; for series i,j = 1 to 3.

thus fit to the data and found adequate; however, the more complex VARMA(1,1,2) model could also be appropriate.

No residual cross-correlations from fitting the unrestricted AR(2) model were significant to lag 2 so moving average parameters were not added to the model. Four additional estimations were made to arrive with a model having 8 parameters (excluding constants in **C**) significant at 2 SE (Table 10.19).

No cross-correlation between residual catch and environmental series from the final estimation was significant (±2 SE) to $\mathcal{L}$=2, suggesting an adequate fit to the data. Also, only 2 residual cross-correlations were significant to lag 5 (Table 10.19), and the model was stationary. Compared to the previous analysis using Nwind, a relatively simple model for pink (Pk) salmon emerged, while the models for sockeye (So) and coho (Co) salmon remained unchanged:

$$\nabla Pk_t = c - \alpha_1 \nabla Pk_{t-1} + \alpha_1 T_{t-1} + \alpha_1 \nabla Co_{t-1} + a_{1t} \qquad (10.33)$$

$$\nabla So_t = c - \gamma_2 \nabla So_{t-2} + a_{2t} \qquad (10.34)$$

$$\nabla Co_t = c - \delta_1 \nabla Co_{t-1} + \delta_1 T_{t-1} + \delta_2 \nabla Pk_{t-2} - \delta_2 \nabla Co_{t-2} + a_{3t} \qquad (10.35)$$

where c, and α_x, γ_x, and δ_x are appropriate elements of **C** and the $\underline{\phi}_x$ matrices in Table 10.19. Note that SEupw and SSEsst both dropped out of the model. Residual variances for pink salmon catch from the two models for $\nabla\mathbf{Z}_t$ are quite different (0.0556 and 0.0858), due in large part to the different number of parameters in (10.30) and (10.33).

Forecasts of pink salmon catch from the VARMA(2,0,0) and VARMA (2,1,0) models for environmental data and salmon catches (Tables F9 and F10) were not better than forecasts from the VARMA(4,0,0) and VARMA(3,1,0) models which did not include environmental data (Table 10.20). Thus, correlations between the catches at lags 3 and 4 are more useful in forecasting this pink salmon series (1981-1985) than were the correlations between catch and selected environmental series at lower lags ($\mathcal{L}$<3). Consideration of different environmental variables (SEupw vs Nwind) led to considerably different models for pink salmon catch.

10.5 Discussion

Vector AR(4) and ARMA(3,1,0) models describe pink, chum, coho, and sockeye salmon catches in Southeast Alaska. The vector AR(4) model typically yielded lower

Table 10.19. Parameter estimates and residual statistics for the vector AR(2) model of **first differences of southern Southeast Alaska** pink, sockeye, and coho salmon catch, 1929-1985, and environmental data set B. $Z_t = [\sqrt{\text{pink}/10^7}, \sqrt{\text{sock}/10^5}, \sqrt{\text{coho}/10^5},$ **SSEwint, SSEsst, SEupw]^T.**

	Estimates	Standard Errors
C	$[-1.20\ \ +0.01\ \ -1.89\ \ +35.2\ \ +51.0\ \ -0.24]^T$	$[0.45\ \ 0.05\ \ 0.72\ \ 0.41\ \ 0.18\ \ 0.93]^T$

$$\underline{\Phi}_1 \quad \begin{bmatrix} -.835 & \cdot & +.188 & +.034 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & -.391 & +.053 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \qquad \begin{bmatrix} .114 & \cdot & .081 & .013 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & .112 & .020 & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

$$\underline{\Phi}_2 \quad \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & -.346 & \cdot & \cdot & \cdot & \cdot \\ +.757 & \cdot & -.368 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \qquad \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & .130 & \cdot & \cdot & \cdot & \cdot \\ .186 & \cdot & .116 & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

Diagonals of $\underline{\Sigma}$ = $[0.086\ \ 0.156\ \ 0.224\ \ 9.139\ \ 1.760\ \ 46.3]$

Residual cross-correlations[a] (ρ_{ij}) at lag $\mathcal{L}$ (first three rows only)

$$\mathcal{L} = \quad \overset{1}{\begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \end{bmatrix}} \quad \overset{2}{\begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \end{bmatrix}} \quad \overset{3}{\begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&-&\cdot&\cdot&\cdot&\cdot \end{bmatrix}} \quad \overset{4}{\begin{bmatrix} \cdot&+&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \end{bmatrix}} \quad \overset{5}{\begin{bmatrix} \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \\ \cdot&\cdot&\cdot&\cdot&\cdot&\cdot \end{bmatrix}}$$

[a] Indicator symbols +, -, and · denote significant positive, significant negative, or non-significant values of ρ_{ij} (±2 SE), when series j leads series i.

Table 10.20. Residual variances (RMS) and relative forecast errors for vector AR models of square root transformed pink salmon catches and environmental data in southern Southeast Alaska. Forecast errors are the median and mean of the absolute values of five one-step-ahead relative forecast errors, and the mean percent relative forecast error (MPE).

		Forecast Error		
Z_t=[pink,chum,sock,coho]; Data from Table 10.9.	RMS	Median	Mean	MPE
AR(4), Z_t	0.0697	17.2	21.0	-19.9
AR(3), ∇Z_t	0.0821	14.0	26.9	-26.9
Z_t=[pink,sock,coho,environ], environ=SSEwint,SSEsst,*Nwind*	RMS	Median	Mean	MPE
AR(2), Z_t	0.0774	40.8	37.3	-21.7
AR(2), ∇Z_t	0.0556	30.9	33.2	-26.5
Z_t=[pink,sock,coho,environ], environ=SSEwint,SSEsst,*SEupw*	RMS	Median	Mean	MPE
AR(2), ∇Z_t	0.0858	38.5	29.5	11.2

RMS (better fit) and forecast pink salmon catch in each area best. The ARMA(3,1,0) model was typically more parsimonious, forecast chum salmon catch best, and except in southern Southeast Alaska also forecast coho and sockeye salmon catch best. Mean one-step-ahead forecast errors for pink, coho, and sockeye salmon catch (from the vector AR(4) model) in southern Southeast Alaska were lower than forecast errors from the best univariate or TFN models developed earlier (Table 8.13). This model thus appears most useful as an alternative to univariate or TFN models for southern Southeast Alaska.

Adding environmental data to the vector models for catch significantly complicated the modeling. Some complications were avoided by using prior information (results from TFN and exploratory VARMA modeling) to select variables for the model. Reasonable assumptions were made to further simplify the analysis, and a modified statistic was employed to aid in identifying the models. Still, model identification was not obvious. Models for both the original data and first differences of the catch data for southern Southeast Alaska yielded forecasts for pink salmon that were no better than forecasts from VARMA models without environmental data.

The catch series are probably influenced by some common factors; otherwise the series would not appear jointly stationary, exhibit (statistical) feedback between themselves, and exhibit significant contemporaneous correlations. One may guess that trends in management, fishing methods, and ecological factors have similar influences on the series, that result in similar patterns in catch over time (Figure 10.1). If some of these variables could be quantified, further application of statistical models similar to those described in this chapter, may be valuable.

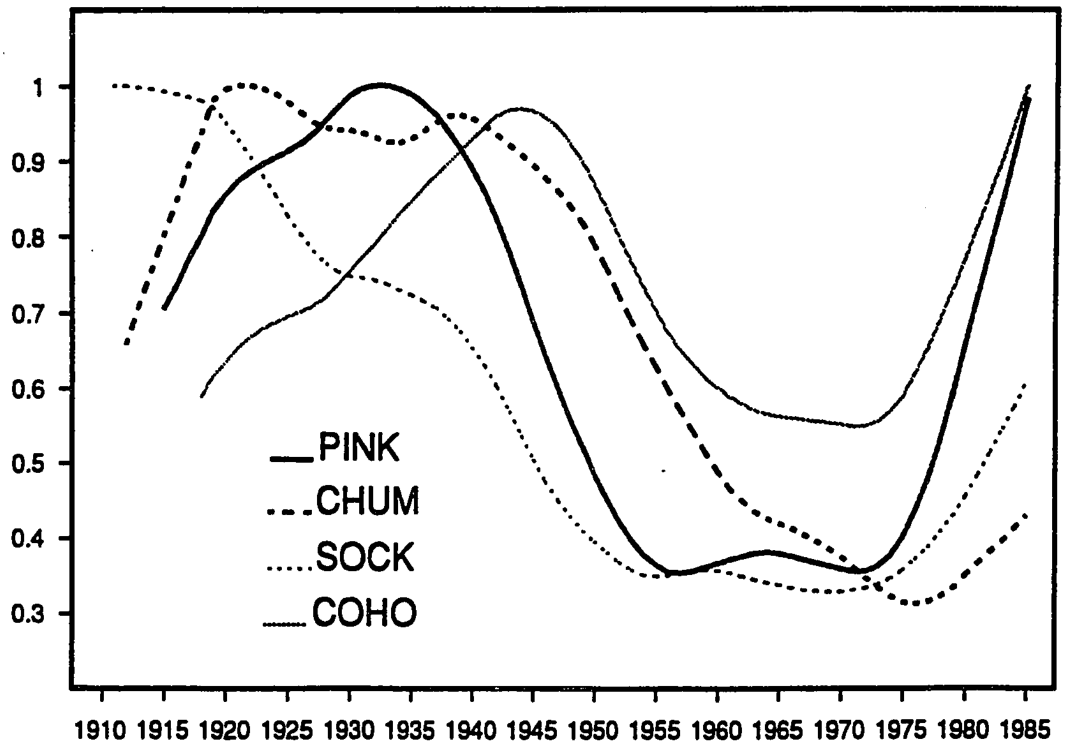


Figure 10.1. Smoothed series of commercial catches of pink, chum, sockeye, and coho salmon in Southeast Alaska (Table A3). Smoothing was done with the LOWESS algorithm (Cleveland 1979, F=0.3). To enhance comparisons, the series were rescaled after smoothing so that the maximum value in each series was 1.

CHAPTER 11
FORECASTING CATCHES OF PACIFIC SALMON IN SOUTHEAST ALASKA

This chapter describes a final test of the methods applied to pink salmon data in southern (SSE), northern (NSE), and Southeast (SE) Alaska. I selected pink salmon because of their commercial importance and relatively simple life history. Relevant data from 1986 to 1990 was updated and model performance in forecasting catches during these years was evaluated. The series used in this analysis are available from the author on request. If the models are good descriptors of the underlying processes of salmon dynamics, then the performance should be similar to 1981 to 1985, as described earlier.

Six models were selected for forecasting catch and comparing forecast errors between 1986-1990. These models include three models from Chapter 5 (the AR(2) and ARIMA(1,1,0) model of catch, and the ARIMA(1,1,0) model of recruitment), the stock-recruit (SR) model from Chapter 6, the best forecasting transfer function-noise (TFN) model from Chapter 8, and the best vector ARMA (VARMA) model from Chapter 10. Forecasts of pink salmon catch by the Alaska Department of Fish and Game (ADF&G) are also included for comparison. Forecasts by ADF&G for Southeast Alaska 1981-1990 were made using multiple regression models and predictor variables that changed from year to year. The history of ADF&G forecasts is summarized in Geiger (1991).

Methods for forecasting catches from forecasts of return are described in Section 11.1. The main results of the analysis follow (Section 11.2), and provide a classic demonstration of forecasting. A discussion that builds on these results and on the successes and failures in earlier chapters is provided in Section 11.3. A summary of conclusions and recommendations for forecasting catches in Southeast Alaska follows.

11.1 Forecasting Pink Salmon Catch from Forecasts of Recruitment

Forecasts of recruitment from SR or from time series models can be manipulated to yield a forecast of catch. One manipulation is to subtract the desired escapement from the forecast of recruitment. This method is used by ADF&G because management strives to realize an escapement goal. Another method is to multiply a recruitment forecast by the fraction typically harvested if the recruitment forecast was realized. In

Southeast Alaska, strong relationships exist between catch and recruitment, and since escapement goals are not met exactly, forecasts derived from expected exploitation rates are an alternative to forecasts derived from escapement goals.

Exploitation (catch divided by recruitment) as a function of estimated recruitment was modeled for each area (SSE, NSE, SE) of Southeast Alaska using two nonlinear models, the Ricker model (6.1) and the Beverton-Holt model (Gulland 1983). Both models were fit to data for 1962 through 1990 using nonlinear least squares (SAS Institute Inc. 1988). Based on the residual mean square error (RMS) statistic, the Ricker models fit each data set best. Parameter estimates (α,β) for the Ricker model were highly significant ($P>0.05$), and the models "fit" the data (Figure 11.1).

The ARIMA(1,1,0) time series model from Chapter 5 (Table 5.13) and the SR model from Chapter 6 (Table 6.4) were used to forecast recruitment in each area. Catch from each model was forecast as the forecast of recruitment minus the escapement goal, and as the forecast of recruitment times the expected exploitation rate. Escapement goals for SSE, NSE, and SE Alaska in 1985 were 15.0, 11.5, and 26.5 million pink salmon, respectively (ADF&G index goals times 2.5, Geiger 1991). The distribution of forecast errors from the exploitation model (1981 and 1985) was less skewed than the distribution from the escapement goal model, and mean absolute percent error (MAPE) was lower by 10, 12, and 6 percentage points in SSE, NSE, and SE Alaska, respectively.

Catch forecasts from the two models of recruitment were then compared with catch forecasts from the four time series models of catch. Forecast errors for all six models (1981-1985) were surprisingly similar within areas, in sharp contrast in SSE and NSE Alaska, and relatively small in Southeast Alaska (Table 11.1, Figure 11.2). Only for Southeast Alaska were forecasts of catch derived from forecasts of recruitment superior to forecasts derived from catch data. Forecasts by ADF&G (1981-1985) had the highest MAPE, although the median absolute and mean percent errors (MPE) were not always highest. The SR, VARMA, TFN, and univariate ARIMA return models were best in at least one situation.

11.2 Forecasts of Pink Salmon Catch, 1986-1990

Forecasts from each of the six models for each area (1986-1990) were made by sequentially adding a new value to each series, re-estimating parameters, and making a new forecast. In some cases model parameters were not significant (±2 SE) after one or more new data points were added to the series. However, except as described below,

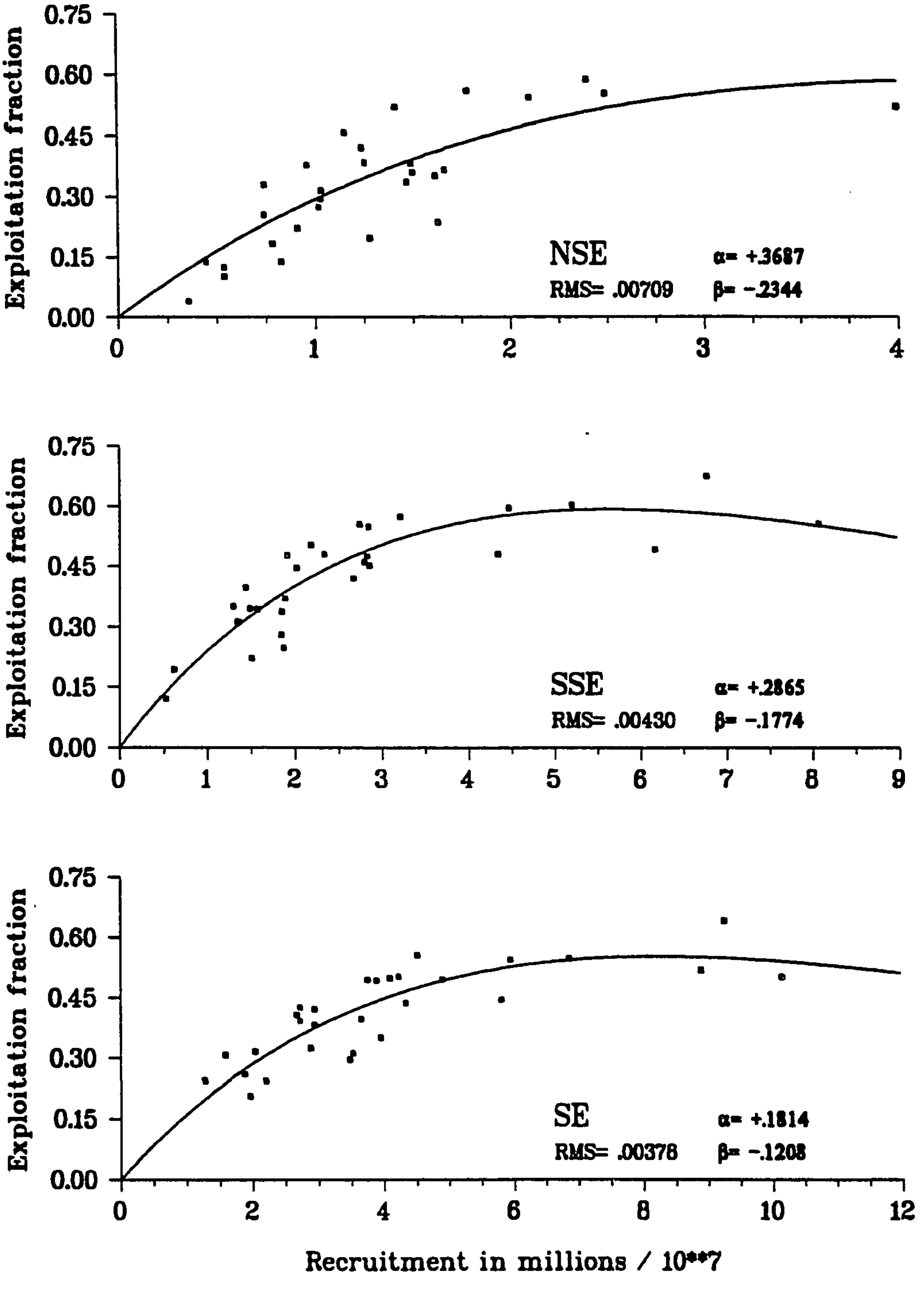


Figure 11.1. Exploitation rate for pink salmon as a function of recruitment to the commercial fisheries in southern Southeast (SSE), northern Southeast (NSE), and Southeast (SE) Alaska, 1962-1990. Ricker models were fit to the data as shown.

Table 11.1. Residual variances (RMS) and relative forecast errors for models of **pink salmon catch** in southern (SSE), northern (NSE), and Southeast (SE) Alaska, 1981-1985. The median and mean of the absolute values of five one-step-ahead relative forecast errors and the mean percent relative forecast error (MPE) are shown for each model.

			Forecast Error		
SSE: Model[a], variable(s)	N[b]	RMS	Median	Mean	MPE
AR(2), catch	LT	0.106	27.3	28.3	-28.3
ARIMA(1,1,0), catch	ST	0.097	20.2	24.9	-24.5
TFN, catch+environ	MT	0.062	38.9	32.2	-13.4
Vector AR(4), catch	LT	0.070	17.2	21.0	-19.9
Stock-Recruit[d], return+environ	ST	0.098[e]	39.9	35.1	6.0
ARIMA(1,1,0)[d], return	ST	0.092[e]	17.5	24.5	-21.2
AK Dept Fish & Game[f]	ST		36.2	37.7	-10.2
NSE: Model[a], variable(s)	N[c]	RMS	Median	Mean	MPE
AR(2), catch	LT	0.074	59.8	50.8	-20.2
ARIMA(1,1,0), catch	ST	0.084	72.4	61.1	-16.9
TFN, catch+environ	LT	0.058	34.1	35.7	-15.3
Vector AR(4), catch	LT	0.069	42.6	46.6	-27.1
Stock-Recruit[d], return+environ	ST	0.210[e]	56.4	70.3	23.2
ARIMA(1,1,0)[d], return	ST	0.080[e]	68.3	48.9	-9.8
AK Dept Fish & Game[f]	ST		67.3	74.4	-36.1
SE: Model[a], variable(s)	N[c]	RMS	Median	Mean	MPE
AR(2), catch	LT	0.135	30.3	30.0	-29.2
ARIMA(1,1,0), catch	ST	0.105	35.9	32.6	-29.0
TFN, catch+environ	LT	0.113	24.7	23.3	-23.3
Vector AR(4), catch	LT	0.091	32.0	29.1	-29.1
Stock-Recruit[d], return+environ	ST	0.067[e]	22.4	19.1	4.4
ARIMA(1,1,0)[d], return	ST	0.112[e]	30.5	27.0	-23.3
AK Dept Fish & Game[f]	ST		37.0	33.0	-25.1

[a] Models from (in order): Table 5.3, Table 5.13, Table 8.2, Table 10.9, Table 6.5, and Table 5.13.
[b] LT=1917-1985; MT=1951-1985; ST=1960-1985. [c] LT=1915-1985; ST=1960-1985.
[d] Forecast of catch=forecast of return times exploitation fraction.
[e] RMS is for model of return. [f] ADF&G 1981-1984; Eggers 1985.

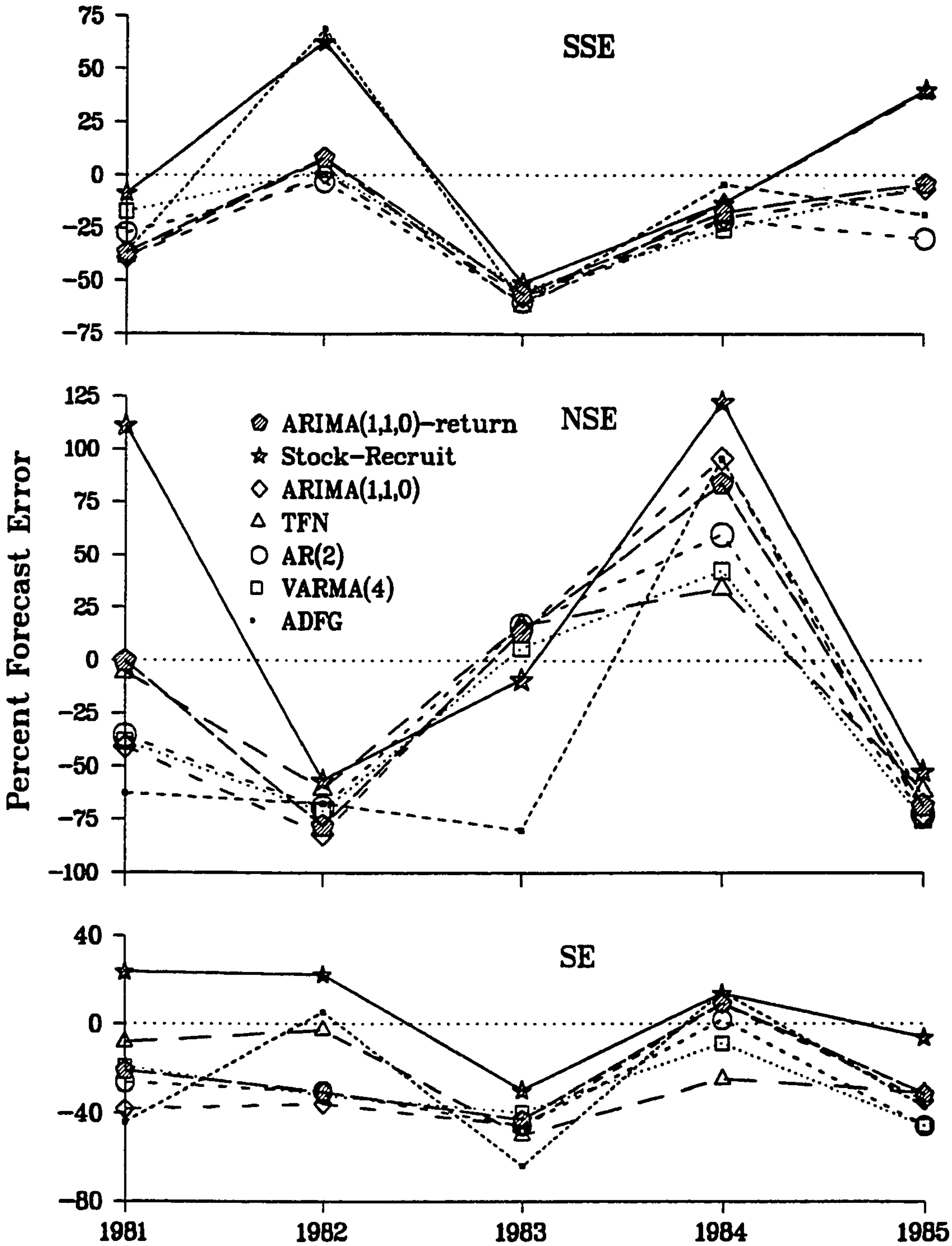


Figure 11.2. Percent error in forecasts of pink salmon catch from seven models for southern Southeast (SSE), northern Southeast (NSE), and Southeast (SE) Alaska, 1981-1986.

model structure was not changed during the validation procedure. The exception was made when the parameter β for density dependent mortality in the SR model (6.4) became significant after a new value was added to the recruitment series. This happened *after* returns from 1988 were available for NSE and SE Alaska, and *after* returns from 1987 were available for SSE Alaska. One-step-ahead forecast errors for each model in SSE, NSE, and SE Alaska (1986 through 1990) are summarized in Table 11.2.

The most significant feature of the recent forecasts (Figures 11.3-11.5) are the astounding errors for 1986 (in NSE Alaska), and in 1987 and 1988 (in SSE and SE Alaska), by all models including those used by ADF&G. Unusually high errors also occurred in several forecasts for 1987 and 1988 in NSE Alaska. The high positive (+) forecast errors denote that catches were much lower than expected. Peak forecast errors in SSE and NSE Alaska were out of phase with each other (different years) and errors for SE Alaska were again smaller than errors for either area. Forecast errors returned to "normal" levels between 1987 and 1989 in NSE Alaska (depending on the model used) but not until 1989 in SSE and SE Alaska. Partial explanations for the extreme forecast errors involve the models and the fisheries in each area.

The high forecast errors from the SR models in 1987 and 1988 are partly explained by noting that record high escapements in 1985 (in SSE, NSE, and SE Alaska) and 1986 (SSE and SE Alaska) were followed by very poor returns two years later (1987 and 1988). This phenomenon (the low returns) is explained as density dependent mortality in the Ricker model (6.1). Forecast errors from the SR models in 1987 and 1988 would thus be much lower if a parameter for density dependent mortality could have been foreseen and included in the models, as shown below. The large percentage error in the 1986 forecast of catch in NSE Alaska also involves the fisheries, in perhaps two different ways. First, significant interceptions of fish bound for NSE Alaska in 1986 might have occurred in SSE Alaska, as suggested earlier (e.g., Section 6.3) to explain the general negative correlation between forecast errors in the two areas. The catch in SSE Alaska in 1986 was roughly 1.8×10^7 pink salmon over forecast while the catch in NSE Alaska was roughly 0.7×10^7 pink salmon under forecast. Second, poor returns to NSE were readily apparent in 1986, and directed fishing for pink salmon was restricted (ADF&G 1987) to conserve stocks; this served to further increase the forecast error.

An explanation for the poor performance of all other (non-SR) models considered in the analysis is trivial; the univariate models cannot forecast low catches or returns from high catches or returns, and auxiliary information included in the multivariate

Table 11.2. Residual variances (RMS) and relative forecast errors for models of **pink salmon catch** in southern (SSE), northern (NSE), and Southeast (SE) Alaska, 1986-1991. The median and mean of the absolute values of five one-step-ahead relative forecast errors and the mean percent relative forecast error (MPE) are shown for each model.

			Forecast Error		
SSE: Model[a], variable(s)	N[b]	RMS	Median	Mean	MPE
AR(2), catch	LT	0.148	81.4	165.8	99.8
ARIMA(1,1,0), catch	ST	0.220	86.6	213.2	151.5
TFN, catch+environ	MT	0.600	77.8	257.6	209.1
Vector AR(4), catch	LT	0.107	67.9	179.2	127.8
Stock-Recruit[d], return+environ	ST	0.166[e]	44.8	222.1	189.9
ARIMA(1,1,0)[d], return	ST	0.217[e]	83.3	240.8	185.0
AK Dept Fish & Game[f]	ST		73.0	170.7	101.9
NSE: Model[a], variable(s)	N[c]	RMS	Median	Mean	MPE
AR(2), catch	LT	0.080	65.7	180.4	152.3
ARIMA(1,1,0), catch	ST	0.095	67.9	184.0	145.4
TFN, catch+environ	LT	0.175	45.9	187.3	143.2
Vector AR(4), catch	LT	0.072	64.2	161.3	126.9
Stock-Recruit[d], return+environ	ST	0.222[e]	239.1	285.0	257.2
ARIMA(1,1,0)[d], return	ST	0.085[e]	62.1	220.4	185.4
AK Dept Fish & Game[f]	ST		57.6	134.8	88.6
SE: Model[a], variable(s)	N[c]	RMS	Median	Mean	MPE
AR(2), catch	LT	0.171	77.5	107.0	56.3
ARIMA(1,1,0), catch	ST	0.218	82.0	133.3	86.5
TFN, catch+environ	LT	0.782	49.1	120.3	81.5
Vector AR(4), catch	LT	0.120	71.9	104.5	54.7
Stock-Recruit[d], return+environ	ST	0.116[e]	61.8	151.5	121.2
ARIMA(1,1,0)[d], return	ST	0.215[e]	79.1	143.6	103.4
AK Dept Fish & Game[f]	ST		70.4	116.8	55.9

[a] Models from (in order): Table 5.3, Table 5.13, Table 8.2, Table 10.9, Table 6.5, and Table 5.13.
[b] LT=1917-1990; MT=1951-1990; ST=1960-1990. [c] LT=1915-1990; ST=1960-1990.
[d] Forecast of catch=forecast of return times exploitation fraction.
[e] RMS for model of return. [f] Eggers 1986; Eggers and Dean 1987,1988; Geiger and Savikko 1989,1990.

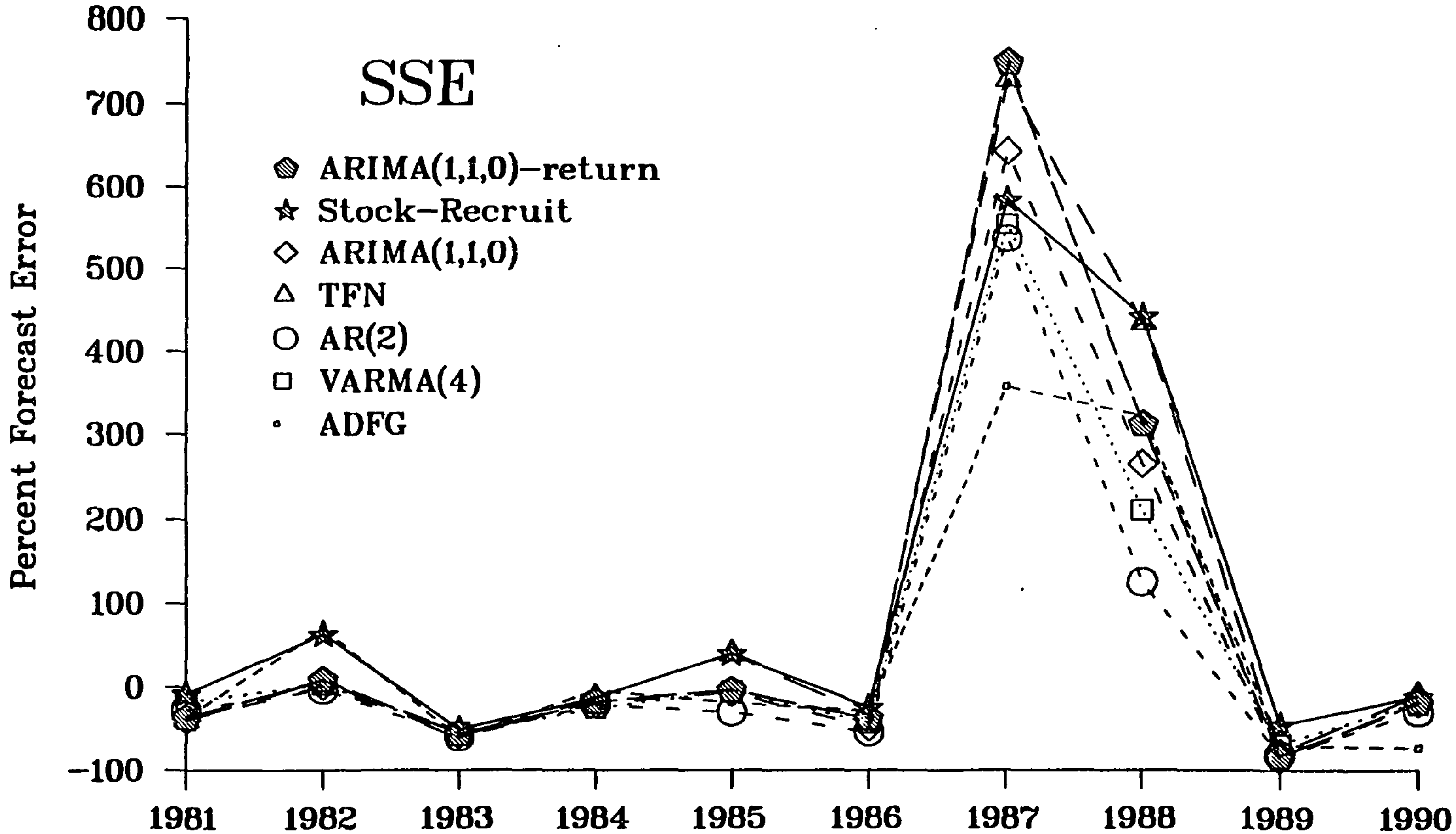


Figure 11.3. Percent error in forecasts of pink salmon catch from seven models for southern Southeast Alaska, 1986-1990.

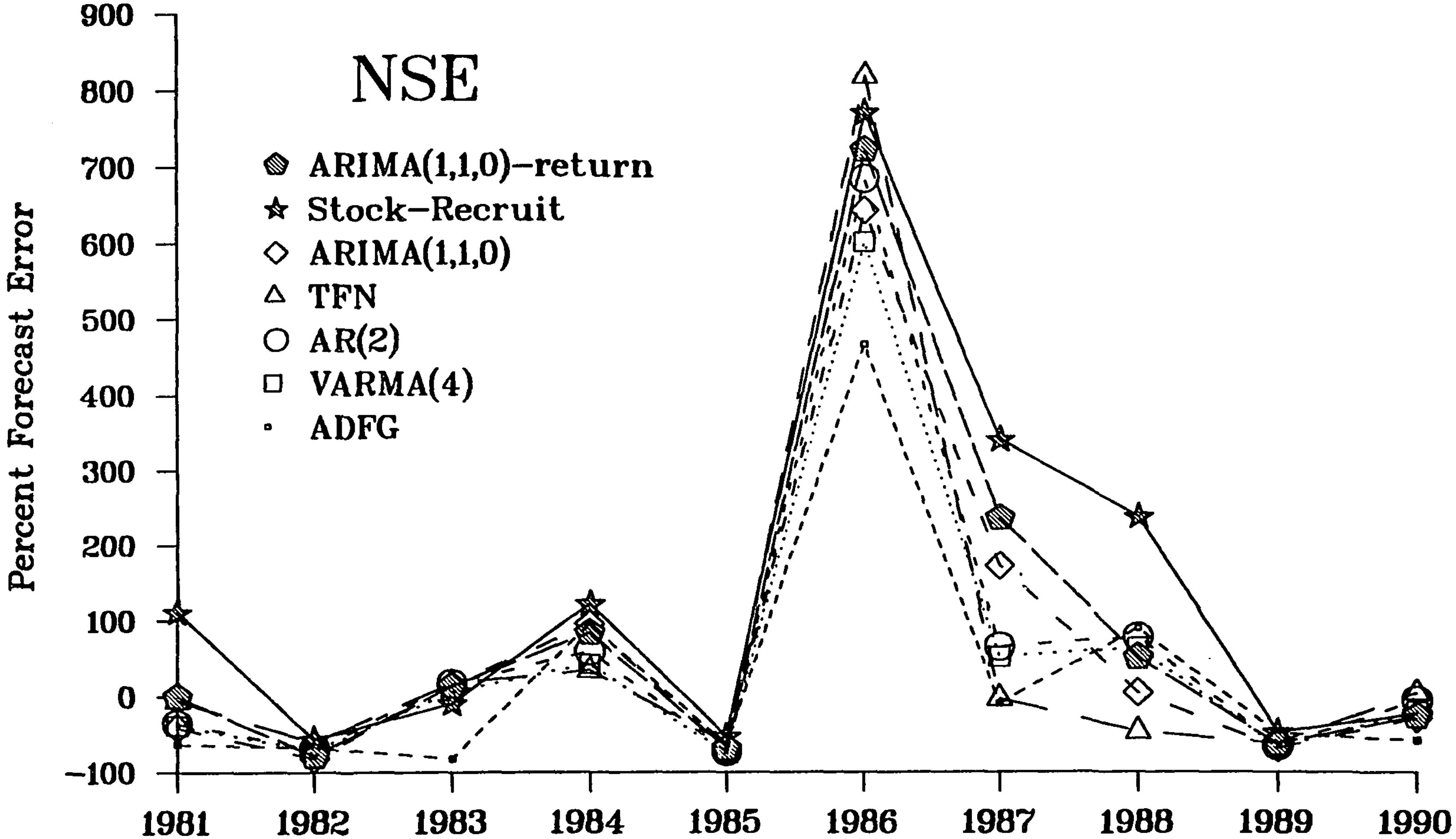


Figure 11.4. Percent error in forecasts of pink salmon catch from seven models for northern Southeast Alaska, 1986-1990.

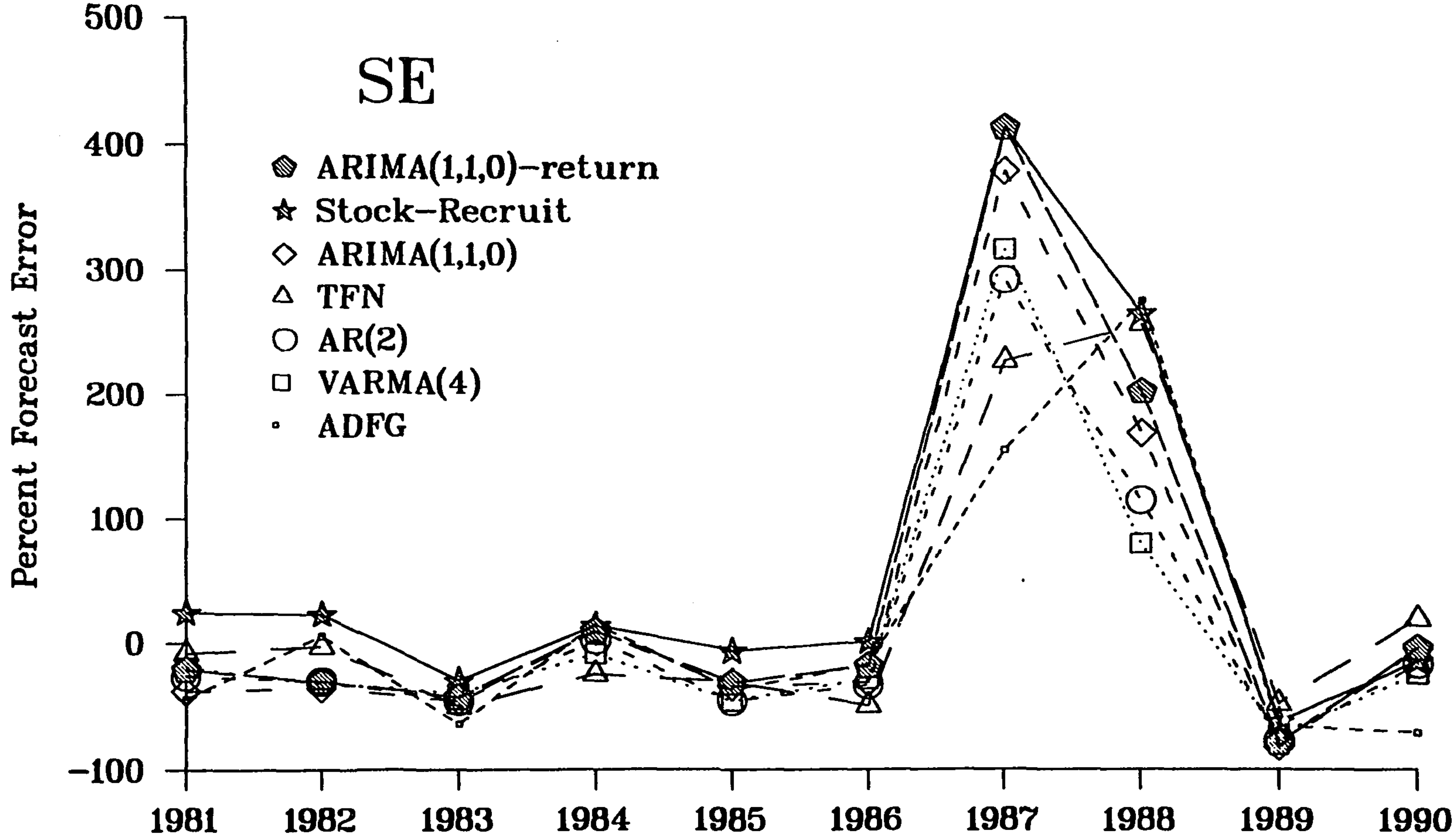


Figure 11.5. Percent error in forecasts of pink salmon catch from seven models for Southeast Alaska, 1986-1990.

models (catch of other species and environmental effects) does not explain the low catches of pink salmon in these years. Thus, it is reasonable to conclude that the time series models could not avoid similar errors if similar circumstances occur in the future. In general, the AR(2) and VARMA(4,0,0) models of catch, which rely heavily on catch at time t-2 (one regeneration period), produced the lowest errors (MAPE) in each area. In contrast, models which relied heavily on data from time t-1 (the TFN noise model for SSE Alaska and the ARIMA(1,1,0) models of recruitment) yielded the highest errors in SSE Alaska and the second highest errors in NSE and SE Alaska (Table 11.2). This occurred, in part, because biased information from t-1 (a catch not generated by the identified ARIMA mechanism) was used to forecast catch at time t. The relative success of the forecasts by ADF&G in NSE Alaska was in part due to data on growth and relative abundance of juvenile pink salmon collected during limited marine surveys.

The question of which models are best for forecasting future catches in each area of SE Alaska depends more on the reasons for the extremely high forecast errors between 1986 and 1988, and whether these errors can be avoided in the future, than the average or median forecast errors between 1981 and 1990. If density dependent mortality is important in describing future pink salmon recruitment in SE Alaska then the linear time series models considered in this study will fail when escapements are very high.

The influence of a parameter for density dependent mortality on forecasts from the SR models for 1987 and 1988 in SSE and SE Alaska, and for 1986-1987 in NSE Alaska was estimated by fixing a value of β in each model (6.3) to the values for 1990 (-0.3904, -0.4430, and -0.2347 for SSE, NSE, and SE Alaska, respectively), re-estimating other parameters, and re-forecasting catches. The forecasts of recruitment and catch from each model were significantly reduced in one or more years (Figure 11.6), and MAPE for catch (1986-1990) was reduced 25% to 60% with β in the model (Tables 11.2 and 11.3). The high error in forecasting catch to NSE Alaska in 1986 is partly explained by restrictive fishing regulations to conserve the stock (see above), not an extreme high error in forecasting the return (Figure 11.6). Thus, high "unexplained" errors remain in forecasts of catch and recruitment in SSE and SE Alaska in 1988. Overall, MAPE for forecasting catch to Southeast Alaska 1981-1990 was 49%, and the first, second, and third quartiles of the forecast errors were 10%, 23%, and 83%, respectively.

Since environment could cause the unusually poor recruitment in 1988, residuals from the fitted stock-recruit models in each area (1962-1990) were cross-correlated with the updated environmental series for Southeast Alaska (Table 3.1) to search for

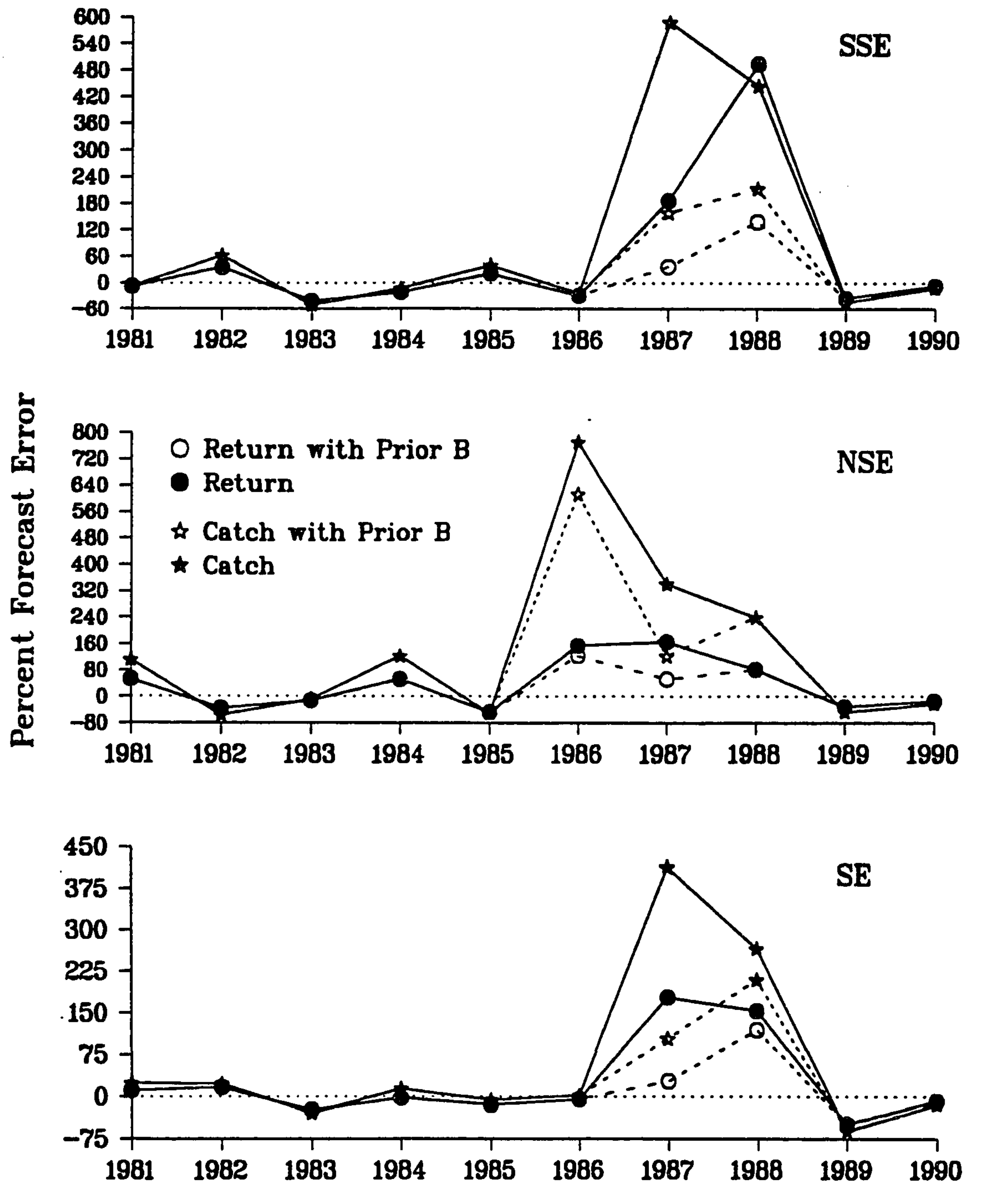


Figure 11.6. Percent error in forecasts of pink salmon catch and recruitment, 1986-1988, from stock-recruit models with and without a parameter (B) for density dependent mortality. Errors from models for southern Southeast (SSE), northern Southeast (NSE), and Southeast (SE) Alaska, are shown.

Table 11.3. Percent errors in forecasting catch and return to fishing areas of Southeast Alaska using stock-recruit[a] models and prior information about density dependent mortality[b], 1986-1990.

SSE	Return Forecast Error		Catch Forecast Error	
yr	PE	APE	PE	APE
86	-29.2	29.2	-24.5	24.5
87	37.3	37.3	159.2	159.2
88	139.0	139.0	213.3	213.3
89	-35.3	35.3	-44.8	44.8
90	-6.9	6.9	-11.3	11.3
medians	-6.9	37.3	-11.3	44.8
means	21.0	49.5	58.4	90.6

NSE	Return Forecast Error		Catch Forecast Error	
yr	PE	APE	PE	APE
86	123.7	123.7	616.1	616.1
87	52.8	52.8	123.3	123.3
88	81.6	81.6	239.1	239.1
89	-31.4	31.4	-47.1	47.1
90	-15.0	15.0	-22.5	22.5
medians	52.8	52.8	123.3	123.3
means	42.3	60.9	181.8	209.6

SE	Return Forecast Error		Catch Forecast Error	
yr	PE	APE	PE	APE
86	-4.9	4.9	1.3	1.3
87	27.3	27.3	103.4	103.4
88	119.3	119.3	209.5	209.5
89	-49.2	49.2	-61.8	61.8
90	-8.6	8.6	-14.0	14.0
medians	-4.9	27.3	1.3	61.8
means	16.8	41.9	47.7	78.0

[a] Models in Table 6.4.
[b] Fixing β to -0.3904, -0.4430, and -0.2347 for SSE, NSE, and SE Alaska, respectively.

unidentified correlates. In northern Southeast Alaska, correlations with inland SST (NSEsst, r=0.41) at lag 1, and stream discharge at lag 2 (NSEdis, r= 0.39) had become significant (±2 SE). Potentially useful correlations with the series for southern Southeast Alaska were not found. Further examination of the environmental series revealed exceptionally low SST in the Northeast Pacific Ocean during 1987 and 1988 at 45°N, and very strong downwelling during June and July (of 1987 and 1988) when juveniles and adults traverse the coastal waters of Southeast Alaska. This information can be considered in a subsequent analysis for forecasting catches to Southeast Alaska.

Other factors may also have contributed to the apparently poor recruitment in 1988. For example, if the near-record escapement in 1986 was significantly under-estimated, the forecast of recruitment in 1988 would be biased high if a Ricker model accurately describes the stock-recruit relationship when escapements are large. Pink salmon from Southeast Alaska might also be harvested in non-Alaskan fisheries, reducing the apparent return. This possibility is suggested in the following discussion, where residuals from SR models for British Columbia (BC) and SE Alaska are compared.

The strong correlation between forecast errors from different models of pink salmon catch and recruitment in Southeast Alaska raise the question of whether the anomalous recruitment (or forecast errors) in Southeast Alaska are correlated with anomalous recruitment in neighboring fisheries. To investigate, returns and escapements of wild stocks of pink salmon in Prince William Sound (PWS) and Kodiak (Eggers et al. 1991) and returns to British Columbia from north of Vancouver Island to Southeast Alaska (statistical areas 1-10, CDFO Salmon Stock Assessment Database, Ben Van Alen, ADF&G, Juneau, personal communication) were fit to the Ricker SR model (Figure 11.7) to obtain a series of residuals for each area. A series for Southeast Alaska (without environmental data) was also constructed. Residuals from the models for SE Alaska and "northern" BC were significantly correlated (r=0.55, P=0.01). However, other residual series were uncorrelated (P>0.05), as seen in the matrix of correlation coefficients

$$
\begin{array}{l c}
 & \begin{array}{cccc} \text{KODIAK} & \text{BC} & \text{PWS} & \text{SE\_AK} \end{array} \\
\begin{array}{l} \text{KODIAK} \\ \text{BC} \\ \text{PWS} \\ \text{SE\_AK} \end{array} &
\begin{bmatrix} 1.00 & & & \\ 0.24 & 1.00 & & \\ 0.17 & -0.03 & 1.00 & \\ 0.33 & 0.55 & 0.24 & 1.00 \end{bmatrix}
\end{array}
$$

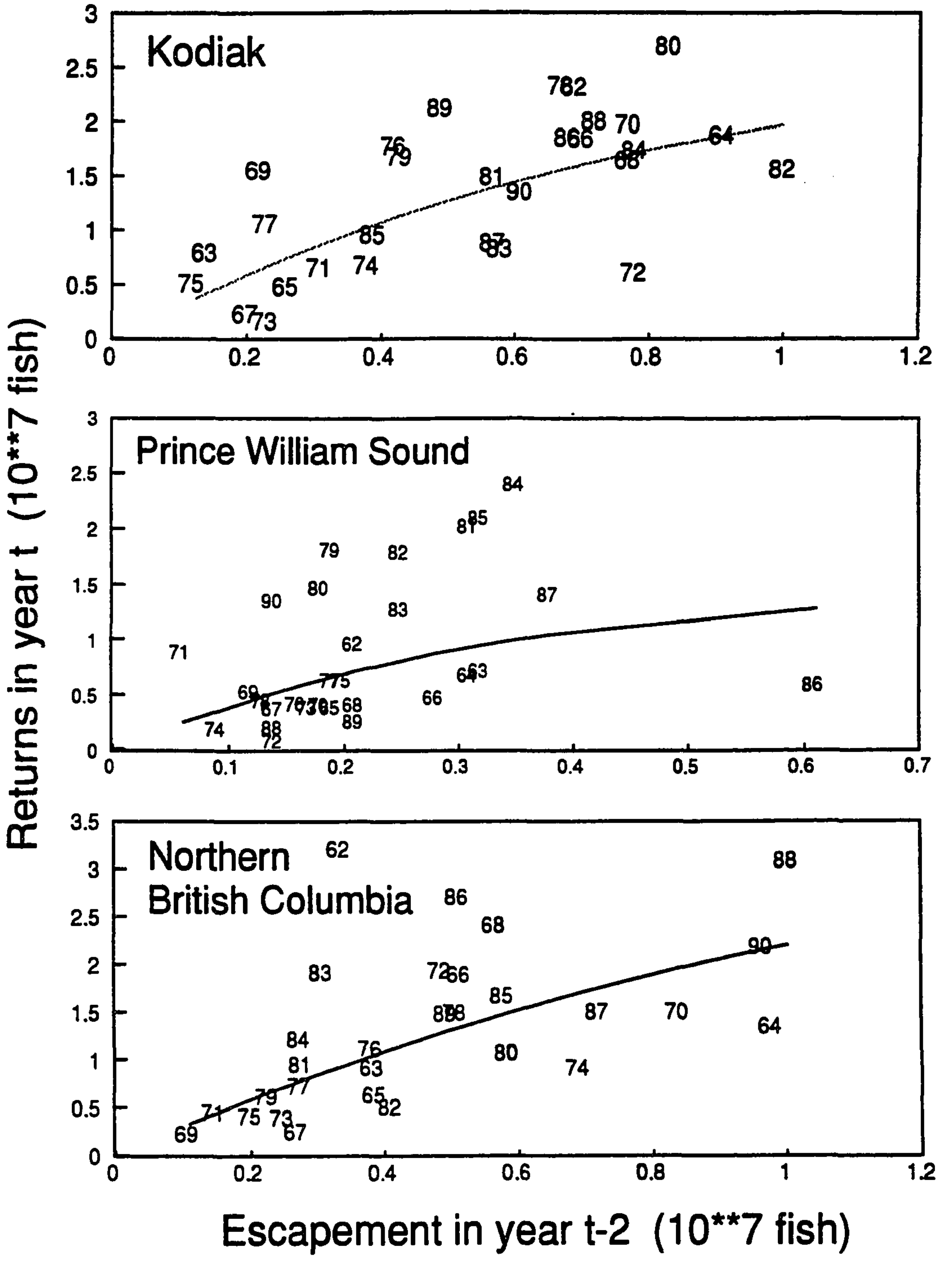


Figure 11.7. Return versus escapement for wild stocks of pink salmon in Kodiak and Prince William Sound Alaska, and for pink salmon returning to British Columbia statistical areas 1-10, 1962-1990. Ricker models were fit to the data as shown.

and plots of the series (Figure 11.8). Except as noted below, the residuals series were also uncorrelated (2 SE) with the series of temperatures in the Northeast Pacific Ocean during fall migrations (SST55s), and residence on the high seas (SSTave, Table 3.1). The exceptions are that fall temperature (SST55s) was correlated (r=0.44) with PWS residuals at lag 1, an SSTave was correlated (r=0.45) with PWS residuals at lag 0.

The lack of correlations between residuals from the stock-recruit models for Southeast Alaska, Prince William Sound, and Kodiak, Alaska (1962-1990) suggest that large-scale phenomena in the Northeast Pacific Ocean are not modulating recruitment to these areas in the same way from year to year. In contrast, the significant correlation between SE Alaska and "northern" BC stocks is suggestive that the population dynamics of these two neighboring stocks are related through common influences by regional environmental phenomena. Unfortunately, these factors are not apparent; residuals from the SR model for BC stocks are uncorrelated (±2 SE) with the environmental series compiled for pink salmon in Southeast Alaska (Table 3.1). Alexandersdottir (1987) noted that similar trends in catch and escapement of pink salmon stocks in SSE Alaska and northern British Columbia have been observed by other investigators.

Because residuals from SR models for pink salmon in Southeast Alaska and British Columbia (Figure 11.8) are similar, significant differences between the series are also of interest. One explanation for the larger opposing deviations in expected returns is that migration routes on the high seas, and in particular as fish approach the coast, vary significantly with temperature and current patterns, so that interceptions in neighboring fisheries sometimes occur. In 1988 for example, returns in "northern" BC (mostly in statistical districts 6-8) were well above that predicted by the SR model while returns in SE Alaska were below predictions (Figures 11.7 and 11.8). Since SST in the Gulf of Alaska was unusually low during 1987-1988, pink salmon bound for SE Alaska may have entered commercial fishing areas by an abnormal, southern route. Although migration patterns of pink salmon within Southeast Alaska and British Columbia have been studied extensively (e.g., Hoffman et al. 1986) offshore migration routes and the extremely high (10^7 fish) interception rates which are required to explain these deviations have apparently not been reported.

11.3 Discussion

In Southeast Alaska emphasis is placed on forecasting pink salmon catch because of the variation in and large economic value of this fishery. Although simple time series

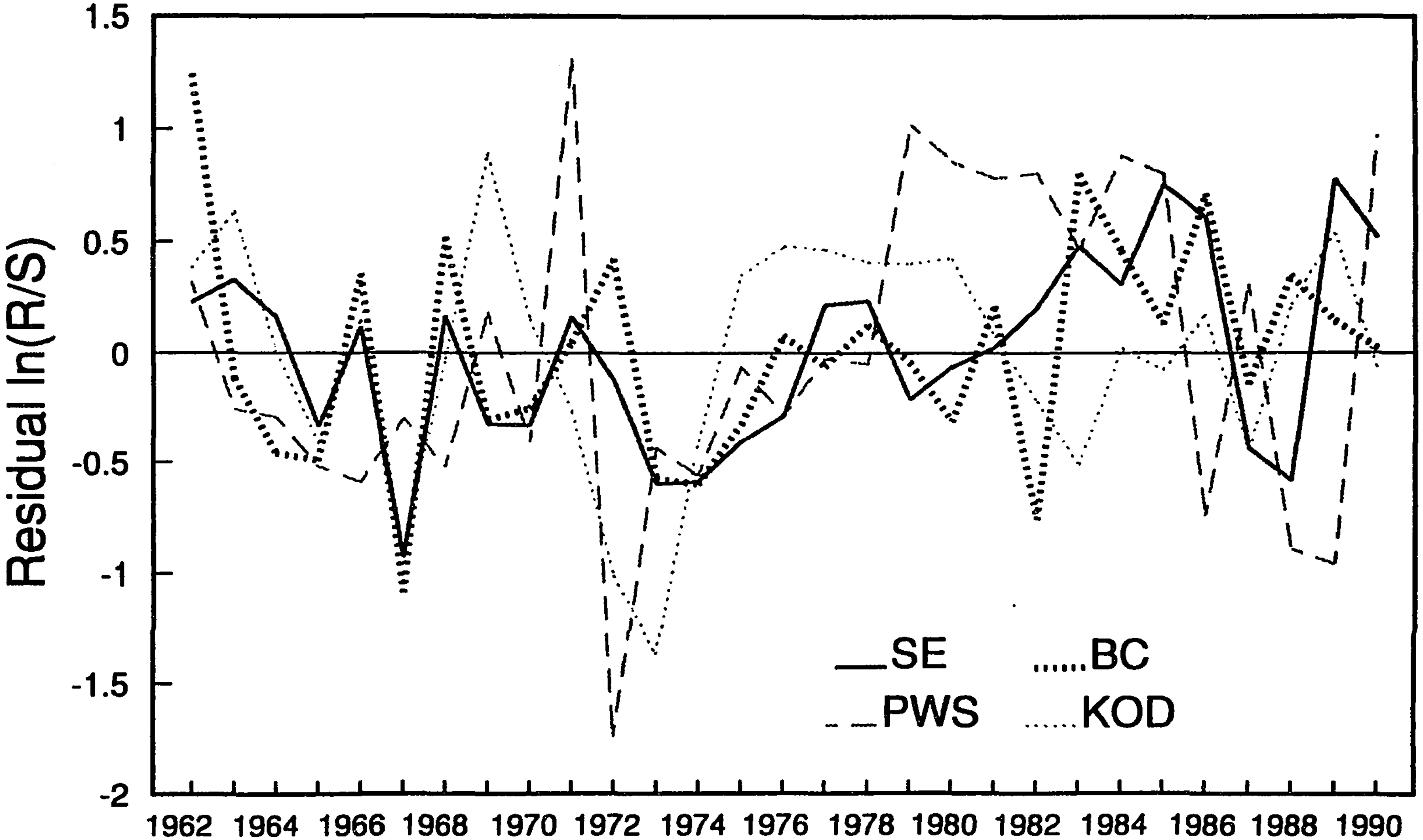


Figure 11.8. Residuals from Ricker models of pink salmon returns to Southeast Alaska (SE), British Columbia statistical areas 1-10 (BC), and wild stocks returning to Prince William Sound (PWS), and Kodiak (KOD), Alaska, 1962-1990.

models of catch, such as the AR(2) model, provided forecasts for 1981 through 1990 that were comparable to forecasts from stock-recruit models using escapement data, the stock-recruit models include nonlinear responses to high escapements that will allow them to solidly outperform time series models in the future when escapements are high. Even so, peak forecast errors for pink salmon catch in Southeast Alaska may reach 200 percent, if data for 1988 are an indicator.

Time series models of chum, sockeye, and coho salmon catches provided forecasts of catch comparable to or better than the preseason projections made by ADF&G for Southeast Alaska, 1981-1985 (Figure 11.9, Table 11.4). The projections by ADF&G have been based on moving averages of recent harvests, projected returns to large river systems in Southeast Alaska, and other data. Forecasts of chum, sockeye, and coho salmon catches to Southeast Alaska can be economically forecast with the methods described in this thesis. Univariate models characterize the trends and cycles in catch data without regard to the underlying processes that influence the series, and should always be constructed prior to more complicated analysis to provide a baseline for subsequent work. Refinements beyond the univariate analysis should be carefully weighted against the need for better forecasts and the risk of spurious correlations, since the costs for data collection and analysis are relatively high.

Multivariate models which include environmental data provide a logical method for improving forecasts of catch. When density dependent effects are important, or when escapement data is available, a model that considers compensatory mortality should be used, as demonstrated in Section 11.2 for pink salmon, and as demonstrated by others (e.g. Noakes et al. 1987, Noakes et al. 1990). The stock-recruit models developed in this study for pink salmon (Table 6.5) include winter air temperature one year prior to catch and inland sea surface temperature two years prior to catch. A relationship between overall survival and winter air temperature is not surprising, while the relationship with SST at lag 2 was recently reported for pink salmon of the odd-year brood line in Prince William Sound (Willette 1985). In this study, the correlation between $\ln(R_t/S_{t-2})$ and SST at lag 2 was strong (r=0.69 to 0.79) for pink salmon of the odd-year brood line in SSE and SE Alaska, and just significant (r=0.44 to 0.49) for the combined brood lines in SSE and SE Alaska (Tables 6.1 and 6.3). The correlation for the odd-year brood line and SST_{t-2} was not significant in northern Southeast Alaska, which could suggest the other correlations are spurious. However, forecasts errors in SSE and NSE Alaska were out of phase, casting doubt on the recruitment and survival indices for NSE. Thus, the

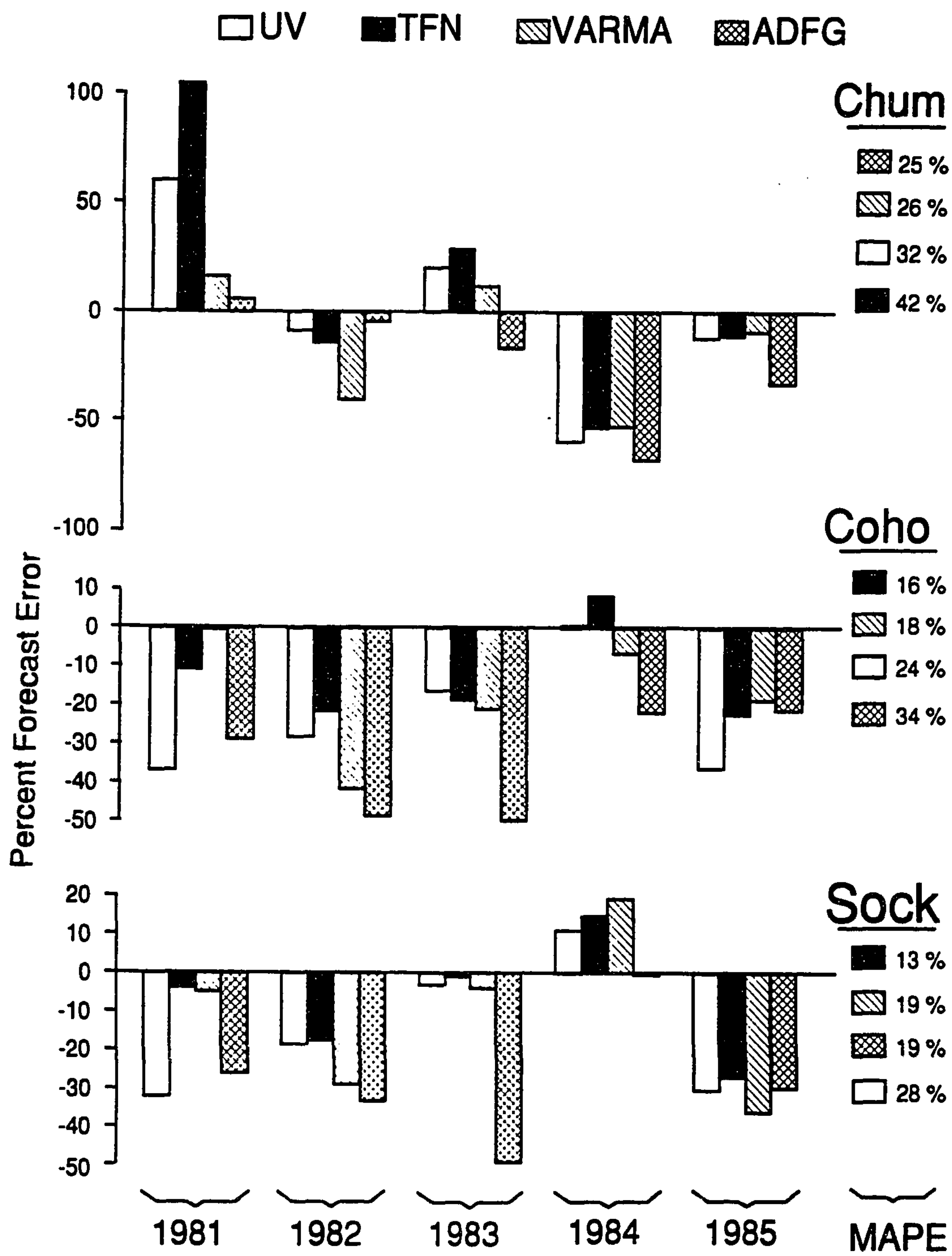


Figure 11.9. Percent forecast errors from univariate (UV), transfer function-noise (TFN), and vector ARMA (VARMA) models, and projections by ADF&G, of chum, coho, and sockeye salmon catches in Southeast Alaska, 1981-1985. Mean absolute percent error (MAPE) for the models are ranked for comparison.

Table 11.4. Percent forecast errors from univariate[a] (UV), transfer function-noise[b] (TFN), and vector ARMA[c] (VARMA) models, and projections by ADF&G[d], of chum, coho, and sockeye salmon catches in Southeast Alaska, 1981-1985.

Chum	UV model Forecast Error		TFN model Forecast Error		VARMA model Forecast Error		ADF&G Projection Error	
yr	PE	APE	PE	APE	PE	APE	PE	APE
81	60.1	60.1	104.8	104.8	16.5	16.5	5.9	5.9
82	-8.5	8.5	-14.2	14.2	-40.3	40.3	-4.4	4.4
83	20.3	20.3	29.1	29.1	12.0	12.0	-16.4	16.4
84	-59.2	59.2	-53.1	53.1	-52.5	52.5	-67.9	67.9
85	-11.5	11.5	-10.6	10.6	-8.8	8.8	-32.7	32.7
medians	-8.5	20.3	-10.6	29.1	-8.8	16.5	-16.4	16.4
means	0.2	31.9	11.2	42.4	-14.6	26.0	-23.1	25.4
Coho	UV model Forecast Error		TFN model Forecast Error		VARMA model Forecast Error		ADF&G Projection Error	
yr	PE	APE	PE	APE	PE	APE	PE	APE
81	-36.9	36.9	-10.9	10.9	-0.5	0.5	-28.9	28.9
82	-28.2	28.2	-21.7	21.7	-41.6	41.6	-48.5	48.5
83	-16.4	16.4	-18.7	18.7	-21.0	21.0	-49.6	49.6
84	0.6	0.6	8.1	8.1	-6.6	6.6	-21.9	21.9
85	-36.3	36.3	-22.4	22.4	-18.7	18.7	-21.2	21.2
medians	-28.2	28.2	-18.7	18.7	-18.7	18.7	-28.9	28.9
means	-23.4	23.7	-13.1	16.4	-17.7	17.7	-34.0	34.0
Sock	UV model Forecast Error		TFN model Forecast Error		VARMA model Forecast Error		ADF&G Projection Error	
yr	PE	APE	PE	APE	PE	APE	PE	APE
81	-31.9	31.9	-3.7	3.7	-4.8	4.8	-25.9	25.9
82	-18.4	18.4	-17.5	17.5	-28.7	28.7	-33.0	33.0
83	-3.0	3.0	-0.9	0.9	-3.9	3.9	-49.0	49.0
84	11.3	11.3	14.9	14.9	19.4	19.4	-0.3	0.3
85	-30.4	30.4	-26.9	26.9	-36.0	36.0	-29.7	29.7
medians	-18.4	18.4	-3.7	14.9	-4.8	19.4	-29.7	29.7
means	-14.5	19.0	-6.8	12.8	-10.8	18.5	-27.6	27.6

[a] Tables 5.6, 5.8, and 5.10. [b] Tables 8.4, 8.6, and 8.9. [c] AR(3)∇Z_t model, Table 10.9.
[d] ADF&G 1981-1984; Eggers 1985.

correlations with SST at lag 2 should be compared with results from still more fisheries where survival data is available (such as in BC) for a more general confirmation.

When stock size and recruitment data are not available, transfer function-noise models provide a framework for modeling single-species catch and environmental data. TFN models also provide the flexibility to model dynamic relationships between variables. However, dynamic transfer functions were not apparent in any TFN models in this analysis, and regression models with lagged inputs and ARIMA models for the remaining noise resulted. Practitioners modeling salmon catch and environmental data with TFN models should thus initially disregard the possibility of a dynamic transfer function, and concentrate on identifying appropriate predictor variables and noise-models.

In this analysis, TFN models could include variables, at any lag from 0 to an average age at maturity plus 1 year, that did not imply an obviously impossible physical relationship between a fish "stock" and it's environment. This facilitated the discovery of important relationships, but increased the potential for including spurious relationships in a model. Forecasts for each species (1981-1985) in most areas were improved relative to forecasts without environmental data (Tables 8.13 and 8.14). Forecasts for chum salmon improved the least (3%) and forecasts for coho salmon improved the most (30%). Also, forecasts for SSE Alaska were hardly improved (2%) while forecasts for NSE Alaska improved most (37%), relative to the univariate models. The relatively high improvement in forecasts for NSE Alaska, and low improvement in SSE Alaska, might be related to the life history of the salmon in each geographic area.

Alexandersdottir (1987) hypothesized that the cold and variable environment at NSE Alaska spawning areas contributes to the fluctuations of abundance and the higher frequency of year class failure in these areas, compared to SSE Alaska where climate is milder and less variable. In this study, more environmental correlates were found for TFN models of catch in NSE Alaska (Table 8.11). Also, catch forecasts for NSE Alaska were consistently more improved by adding environmental data to the models than were forecasts for SSE Alaska (Table 8.14). Some, but not all of the variables identified in the TFN models relate to freshwater environments, and provide a practical result of Alexandersdottir's ideas.

Incorporating environmental data into models of catch can be problematic. For example, stock-recruit models for pink salmon returns in SSE, NSE, and SE Alaska (1962-1985) each include winter air temperature. In contrast, TFN models for pink salmon catch did not include air temperature, except for SSE Alaska after that series was truncated to begin in 1951 (because significant correlations with environmental data were absent using long-term catch data). In addition, forecasts from the TFN model for pink salmon catch in SSE Alaska were not improved relative to a univariate model. Thus, important environmental variables, such as winter air temperature, may not be identified from long-term catch records, and may not improve forecasts from short-term series.

Significant relationships exist between the catches of Pacific salmon in Southeast Alaska. These relationships were explored and quantified with vector ARIMA models, and forecasts of pink, chum, coho, and sockeye salmon catches made with models were comparable to forecasts provided by other methods, 1981-1985 (Tables 11.1 and 11.4, Figure 11.9). Although density dependent responses to large escapements after 1985 probably distorted forecasts of pink salmon catches, the method offered unique insights and robust forecasts of the series, which suggests that application of the methodology to related, multispecies data sets may provide good forecasts of the series.

Feedback between pink and coho salmon catches is indicated in the VARMA models for Southeast Alaska. First, the correlations "suggest" that large catches (and thus escapements) of pink salmon in year t-2 tend to indicate large catches of coho salmon in year t. Since coho salmon smolts prey on young pink salmon (Heard 1991, Sandercock 1991) the survival of coho salmon smolt may significantly depend on abundance of pink salmon fry, as both species enter marine waters. Secondly, large catches of coho salmon tend to indicate small catches of pink salmon two years later. This may indicate that large returns of coho salmon in year t occur at a significant expense of the pink salmon returning at the same time, and as a result smaller returns of pink salmon occur two years later. These statistical relationships can be explored in other data sets to provide a more robust conclusion regarding their importance, and thus the implications to forecasting and fisheries science.

Vector ARMA models which considered relationships between catches of different species and environmental data proved very difficult to identify. This occurred partly because competing influences and spurious correlations among the vector of variables confounded selection of a model describing the important relationships in the system. Similar difficulties occurred when attempting to identify TFN models with several variables considered simultaneously. I attempted to resolve some of these problems by simplifying the model, and incorporating auxiliary information, such as the physical impossibility of feedback from fish to the environment, into the analysis. However, the resulting models yielded poor forecasts of pink salmon catch. This general problem of model identification presents serious difficulties, since unless the important variables are known or correctly assumed in advance, incorrect identifications and poor forecasts can result.

The idea that simple models that accurately predict recruitment from observed environmental changes are unlikely, because abiotic and biotic environments are related in non-linear ways to forcing functions that vary over a wide range of space and time scales (Wooster and Bailey 1989), is certainly germane to this thesis. The problem of forecasting salmon catches encompasses these difficulties, and many others, including the need for better information on the spatial distribution of fish stocks over time.

Regardless of the difficulties, similarities between forecasts from different models is striking, and variables that presumably are missing from current forecast models might be apparent in future analysis. Also, trends in salmon catches (Figure 10.1) show similar, U-shaped, patterns over time. This U-shaped pattern is present for salmon species across Alaska (Marshall and Quinn 1987). If the catch series were independent realizations of independent processes, these similar trends would be unlikely. Such consistencies suggest that common processes not explained by simple statistical models drive salmon population dynamics.

New hypotheses including effects of climate, overfishing, species succession, and habitat loss, will and should be advanced to explain long-term trends in catch and abundance data. Variables that mirror long-term trends in catch and abundance data may not provide substantial improvements in pre-season forecasts of catch and abundance, however, because statistical bias (from not including the variables) in current forecast models may be small over the short term, compared to the remaining interannual variation. Thus, if recruitment of a cohort of salmon is driven largely by events during the earliest life stages, as is commonly presumed, emphasis on the collection of data for testing hypothesis that link environmental variations affecting survival at these life stages are most important to solving problems in forecasting salmon catch and abundance.

11.4 Summary of Conclusions

1) Time series analysis provides forecasts of salmon catch in Southeast Alaska that are equal or better than forecasts from competing models as long as strong density dependent mortality is not operating in the fisheries. When this occurs, stock-recruit relationships are required to avoid forecasting catches with very high error.

2) Forecasts based on long-term series of catch biomass landed were similar to forecasts based on long-term series of catch in numbers landed.

3) Time series analysis is most suited to forecasting catches of chum, coho, and sockeye salmon in SE Alaska. Mean absolute percent error in forecasting catch (MAPE, 1981-1985) was about 30% for chum salmon, and 20% for coho and sockeye salmon.

4) Stock-recruit models which include environmental data should provide the best method of forecasting pink salmon returns to SE Alaska. Thus, ADF&G should strive to obtain the best escapement database possible. Errors in forecasts of catch and recruitment in SSE and NSE Alaska tended to oppose each other and cancel between 1981 and 1985. Thus, ADF&G may lower its forecast error by forecasting only the catch (and returns) to SE Alaska (say Districts 101-116). A district-by-district synopsis of previous brood-year escapements, escapement goals, and current management objectives can be included with each forecast to provide the information that will guide management of the fishery in each district during the approaching year.

5) A hypothesis to explain the opposing deviations in pink salmon forecast errors for SSE and NSE Alaska is that fish bound for one area are intercepted in another area. Investigation of pink salmon entry patterns into Southeast Alaska as a function of environmental conditions might reveal relationships useful for management, and perhaps to help achieve escapement goals in NSE Alaska in years of low abundance.

6) Forecasts of pink salmon catch in SE Alaska that were derived from forecasts of recruitment times an expected exploitation rate were superior to forecasts of catch derived from forecasts of recruitment minus an escapement goal. ADF&G should therefore adopt this method for forecasting catch.

7) Extremely large errors in forecasting pink salmon in Southeast Alaska, 1986-1988, may be explained by a failure to account for density dependent mortality. Simulation of forecasting the fisheries (1986-1988) with prior model of density dependence was used to provide estimates of the distribution of error in forecasting pink salmon catch in SE Alaska in the future; based on forecasts for 1981-1990, mean error

(MAPE) is 49%, and first, second, and third quartiles for the forecast errors are 10%, 23%, and 83%.

8) Powerful "unexplained" shocks characterize the time series of forecast errors observed in this analysis. Patterns in the forecast errors are not significantly changed according to the models used, and thus probably result from environmental influences not considered in the analyses, such as influences on short time and space scales.

9) Relatively large errors in forecasting catch and recruitment of pink salmon in 1988 remained after the simulation that assumed a model for density dependent mortality. Explanations for the error in 1988 include: a) extremely low winter SST at 45^{o}N during 1987 and 1988; b) extremely strong downwelling along SE Alaska during June-July 1987 and 1988; c) interception of adult pink salmon in northern British Columbia during 1988; and d) underestimating the spawning escapement in 1986.

10) The hypothesis that SST experienced by adult pink salmon of the odd-year brood line during their last months at sea strongly influences survival of their progeny (Willette 1985) is moderately supported with data from Southeast Alaska. An analysis to estimate the benefit of including this relationship in future forecast models, relative to other variables (such as SST at lag 1) should be conducted. As part of the analysis, the advantages of forecasting pink salmon returns (with stock-recruit models) and separate- and combined- brood lines should be compared.

11) Improved forecasts of pink salmon returns to Southeast Alaska might depend on improved estimates of escapement, and new environmental indices. Useful indices of peak freshwater discharges might, for example, be constructed from existing data.

12) Significant correlations exist between different species of salmon in Southeast Alaska. Models which include these correlations can be used to provide good forecasts of catch or abundance when density dependent effects are not important in the data. Correlations for Southeast Alaska indicate that catches of pink and coho salmon are related at lag 2 and exhibit "feedback". The statistical relationship might occur as the result of predation on young pink salmon by coho salmon smolt. Similar correlations can be sought in other data sets to provide a more robust conclusion for the relationship.

13) Residuals from stock-recruit models of pink salmon escapement and returns to Southeast Alaska, Prince William Sound, and Kodiak, Alaska (1962-1990) are not significantly correlated with each other, suggesting that large-scale phenomena in the Northeast Pacific Ocean is not modulating recruitment to these areas in the same way from year to year. In contrast, residuals from Southeast Alaska and British Columbia statistical areas 1-10 are significantly correlated ($r=0.55$, $P=0.01$), suggesting that regional phenomena influence these stocks in a similar fashion. The residual series for British Columbia were, however, uncorrelated with environmental data collected for pink salmon.

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APPENDICES

Table A1. Estimates of **numbers** of pink, chum, sockeye, and coho salmon landed in the commercial fisheries of **southern** Southeast Alaska, 1911-85.

	Catch in Numbers			
Year	Pink	Chum	Sockeye	Coho
1911			1,047,660	
1912		2,694,314	809,321	
1913	18,485,393	1,401,927	393,790	
1914		3,829,561	826,902	
1915	19,494,112	2,457,220	801,977	
1916		2,573,020	615,453	
1917	17,267,114	3,954,525	661,553	
1918	21,898,973	2,754,202	815,889	
1919	17,155,078	4,216,061	1,259,094	
1920	10,492,691	4,549,727	975,140	
1921	5,561,698	657,260	335,159	
1922	18,784,538	2,353,105	687,838	
1923	30,099,479	2,546,446	1,037,660	
1924	20,294,953	4,471,250	1,078,625	
1925	23,339,367	4,547,768	692,056	
1926	19,445,288	2,727,631	843,478	
1927	2,584,436	627,354	575,177	
1928	18,061,650	2,830,253	453,893	
1929	12,999,854	1,032,374	623,680	849,803
1930	21,227,914	966,936	780,038	1,284,643
1931	13,567,278	1,670,538	882,861	722,367
1932	14,784,063	2,724,149	626,133	483,514
1933	15,244,909	1,649,663	412,239	692,283
1934	35,204,290	1,068,389	455,682	1,075,669
1935	22,981,957	2,917,050	735,664	1,197,558
1936	37,428,041	3,726,387	1,215,393	1,094,318
1937	20,988,418	3,042,379	1,056,234	866,523
1938	20,206,905	2,815,033	1,071,667	1,359,089
1939	17,452,847	1,843,361	1,098,081	714,052
1940	18,493,159	2,191,528	851,072	1,106,512
1941	37,016,456	1,592,449	1,007,974	1,563,426
1942	19,609,962	3,156,051	953,593	1,413,983
1943	13,165,433	3,136,439	532,549	1,272,531
1944	9,948,654	3,048,299	823,382	940,373
1945	16,294,419	1,779,663	826,395	1,989,458
1946	21,317,909	2,401,505	402,349	1,832,867

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Table A1. (p. 2 of 2).

Year	Catch in Numbers			
	Pink	Chum	Sockeye	Coho
1947	10,680,834	2,121,696	249,937	997,385
1948	12,770,432	3,094,352	243,922	1,324,095
1949	33,980,994	1,953,423	220,814	1,363,507
1950	7,736,960	3,340,341	245,730	1,030,789
1951	16,392,654	1,806,516	280,853	1,257,043
1952	6,334,901	2,497,921	457,218	637,452
1953	3,797,906	1,466,254	606,086	525,414
1954	6,463,394	987,846	444,098	615,190
1955	5,248,347	388,239	256,897	466,920
1956	10,076,425	1,535,430	336,973	365,646
1957	4,683,257	1,446,238	520,433	488,822
1958	6,460,631	1,177,666	561,719	499,586
1959	3,569,329	541,615	417,573	354,533
1960	1,541,859	521,450	210,523	293,631
1961	3,874,636	1,044,202	212,274	399,056
1962	11,007,292	971,129	346,492	642,042
1963	5,145,235	637,214	298,758	385,733
1964	11,258,989	1,192,564	466,225	722,368
1965	5,710,456	289,060	485,409	593,436
1966	15,649,703	705,597	445,347	598,490
1967	641,537	289,818	579,939	168,760
1968	15,200,702	1,263,159	309,351	658,189
1969	1,197,689	69,843	248,726	120,115
1970	5,411,624	643,891	185,064	282,584
1971	6,247,585	704,304	236,743	431,107
1972	9,153,088	1,029,698	462,441	823,329
1973	4,555,106	791,097	421,866	350,951
1974	4,220,925	695,492	346,022	641,918
1975	3,330,214	373,032	114,792	270,553
1976	5,157,427	509,214	256,569	294,822
1977	11,242,198	427,454	647,668	326,863
1978	18,424,978	648,631	455,192	695,794
1979	6,992,031	330,403	552,175	546,606
1980	12,907,264	842,042	742,930	549,040
1981	13,469,296	351,542	719,990	640,756
1982	12,916,865	840,031	842,088	821,582
1983	31,424,100	513,600	943,700	866,200
1984	20,900,600	1,831,100	647,600	665,700
1985	30,472,700	1,300,600	1,111,700	1,198,400

Table A2. Estimates of **numbers** of pink, chum, sockeye, and coho salmon landed in the commercial fisheries of **northern** Southeast Alaska, 1911-85.

Year	Catch in Numbers			
	Pink	Chum	Sockeye	Coho
1911			1,333,215	
1912			1,569,982	
1913			1,260,084	
1914			2,129,958	
1915	10,686,762		1,579,007	
1916	10,595,990		1,316,486	
1917	22,964,480		1,464,525	
1918	17,261,930	6,598,371	1,536,183	
1919	7,151,164	5,052,428	1,502,385	
1920	7,581,383	4,063,641	1,265,129	
1921	2,131,755	1,189,572	642,117	
1922	5,143,651	1,375,511	827,119	
1923	9,471,913	1,359,572	1,001,835	
1924	9,417,114	2,795,250	1,027,325	
1925	4,800,078	3,638,047	947,953	
1926	12,499,941	3,373,780	990,978	
1927	5,478,506	1,591,324	626,972	
1928	17,655,238	2,038,935	685,793	943,965
1929	8,708,941	1,592,845	976,940	390,893
1930	22,182,953	1,741,568	1,494,124	629,876
1931	13,676,252	1,180,208	660,601	429,732
1932	7,761,287	2,866,552	705,906	708,259
1933	10,419,920	2,894,861	441,257	397,925
1934	15,015,809	2,733,706	430,857	642,651
1935	7,178,091	2,164,917	750,524	416,401
1936	13,150,392	3,878,483	939,558	498,575
1937	14,050,677	2,509,407	903,383	355,653
1938	9,952,654	1,740,035	1,088,950	639,570
1939	6,228,085	1,545,170	1,063,494	323,813
1940	10,492,983	2,431,948	484,990	501,789
1941	22,977,799	1,362,000	423,807	611,019
1942	13,459,113	2,285,416	454,963	611,780
1943	4,844,734	3,696,761	453,652	300,436
1944	9,331,682	3,832,736	715,648	274,579
1945	5,344,915	1,534,419	623,420	424,932
1946	3,441,567	1,607,685	369,913	410,544

- Continued -

Table A2. (p. 2 of 2).

Year	Catch in Numbers			
	Pink	Chum	Sockeye	Coho
1947	3,336,008	1,235,417	367,189	473,683
1948	1,482,282	903,518	198,767	716,112
1949	9,922,099	940,536	191,152	871,750
1950	1,640,580	1,432,098	222,386	555,838
1951	5,792,237	2,311,166	390,473	1,925,482
1952	3,430,689	1,668,029	351,740	918,311
1953	1,174,702	2,060,042	658,635	487,655
1954	2,406,036	3,239,726	647,672	888,436
1955	4,059,939	1,116,384	368,391	669,715
1956	3,634,645	1,142,298	469,502	420,451
1957	2,158,163	1,934,397	436,029	666,564
1958	3,315,481	1,591,465	402,850	356,991
1959	4,269,464	711,788	385,093	530,633
1960	1,429,196	485,211	329,444	305,857
1961	8,697,804	1,503,547	449,281	360,049
1962	550,192	1,007,340	345,076	390,996
1963	13,920,884	830,851	326,452	742,912
1964	7,282,081	737,918	365,463	695,736
1965	5,165,053	1,180,549	477,174	829,408
1966	4,787,072	2,564,165	423,411	561,401
1967	2,437,182	1,516,123	303,171	577,180
1968	9,882,380	1,367,204	440,644	762,409
1969	3,608,082	476,640	445,053	416,752
1970	5,241,642	1,794,685	370,675	437,554
1971	3,016,903	1,236,779	257,297	442,771
1972	3,243,675	1,904,349	322,792	629,584
1973	1,882,973	1,032,080	461,302	442,687
1974	663,515	982,873	258,738	557,607
1975	616,235	309,818	57,107	119,131
1976	143,590	513,914	208,514	476,588
1977	2,523,085	302,210	251,852	517,842
1978	2,781,916	213,283	202,371	809,803
1979	3,831,959	550,017	356,517	615,305
1980	1,428,292	788,928	218,313	450,172
1981	5,360,937	487,339	209,856	601,038
1982	11,317,931	512,751	438,891	1,078,637
1983	6,046,900	670,800	472,300	1,018,000
1984	4,901,900	2,184,300	454,800	1,083,200
1985	20,499,400	1,953,900	504,000	1,147,600

Table A3. Estimates of **numbers** of pink, chum, sockeye, and coho salmon landed in the commercial fisheries of **Southeast** Alaska, 1911-85.

	Catch in Numbers			
Year	Pink	Chum	Sockeye	Coho
1911			2,896,988	
1912		5,342,331	3,018,060	
1913		2,459,777	2,218,591	
1914		5,444,154	3,501,203	
1915	30,351,380	3,593,040	2,825,543	
1916	19,940,350	4,741,634	2,381,350	
1917	40,327,465	6,851,774	2,622,899	
1918	39,287,711	9,352,573	2,821,198	1,629,366
1919	24,330,891	9,268,489	3,262,799	1,804,055
1920	18,121,431	8,613,368	2,743,624	1,148,051
1921	7,735,444	1,846,832	1,498,933	911,568
1922	24,001,889	3,728,616	1,900,123	1,258,885
1923	39,879,249	3,912,562	2,410,357	1,342,071
1924	30,029,343	7,266,500	2,506,115	1,214,898
1925	28,246,398	8,188,085	1,843,518	1,211,862
1926	32,193,383	6,105,808	2,044,708	1,184,658
1927	8,163,332	2,219,770	1,444,563	1,284,537
1928	36,051,196	4,871,346	1,350,871	2,159,409
1929	21,848,494	2,626,905	1,901,461	1,368,442
1930	43,483,232	2,708,504	2,587,439	1,998,507
1931	27,243,530	2,850,746	1,823,085	1,152,099
1932	22,605,600	5,593,734	1,652,065	1,389,406
1933	25,783,195	4,547,402	1,010,460	1,223,081
1934	50,327,890	3,805,510	1,241,883	1,956,014
1935	30,247,606	5,083,541	1,892,836	1,759,654
1936	50,747,387	7,605,896	2,403,397	1,799,813
1937	35,166,387	5,556,010	2,187,191	1,399,754
1938	30,288,240	4,556,394	2,535,417	2,199,625
1939	23,721,956	3,388,759	2,487,146	1,122,183
1940	29,093,692	4,624,767	1,507,340	1,838,309
1941	60,061,213	2,959,482	1,674,412	2,515,069
1942	33,127,200	5,441,724	1,566,489	2,211,103
1943	18,038,752	6,833,316	1,123,759	1,680,198
1944	19,344,068	6,881,172	1,722,276	1,306,203
1945	21,654,516	3,318,481	1,683,289	2,587,615
1946	24,821,810	4,010,237	888,241	2,366,848

- Continued -

Table A3. (p. 2 of 2).

Year	Catch in Numbers			
	Pink	Chum	Sockeye	Coho
1947	14,041,563	3,360,303	746,170	1,546,079
1948	14,352,448	4,004,499	524,525	2,145,853
1949	43,920,676	2,894,344	489,799	2,279,890
1950	9,423,824	4,778,742	552,202	1,651,905
1951	22,220,113	4,123,010	819,621	3,310,226
1952	9,802,657	4,178,549	919,316	1,743,753
1953	4,981,409	3,541,901	1,376,454	1,163,581
1954	8,909,481	4,243,671	1,220,157	1,770,807
1955	9,333,972	1,528,202	747,330	1,338,477
1956	13,728,271	2,701,261	914,778	916,542
1957	6,857,895	3,413,051	1,071,257	1,218,479
1958	9,837,907	2,787,025	1,008,235	955,349
1959	7,851,298	1,291,409	890,638	1,024,390
1960	2,985,021	1,019,152	588,288	720,808
1961	12,637,503	2,559,269	744,484	889,419
1962	11,585,176	1,996,383	772,236	1,222,549
1963	19,145,299	1,478,744	677,921	1,274,508
1964	18,581,462	1,936,151	923,923	1,587,910
1965	10,879,934	1,473,867	1,085,318	1,548,265
1966	20,438,170	3,273,157	1,054,119	1,227,305
1967	3,111,251	1,810,412	971,541	866,226
1968	25,085,399	2,644,259	830,775	1,543,095
1969	4,869,865	561,418	811,576	596,490
1970	10,657,030	2,445,686	667,908	758,667
1971	9,344,805	1,946,102	623,252	914,382
1972	12,399,784	2,942,365	916,720	1,508,534
1973	6,455,162	1,832,173	1,011,453	836,348
1974	4,888,753	1,682,603	687,398	1,278,179
1975	4,026,520	686,615	245,191	427,357
1976	5,329,565	1,030,877	595,259	823,662
1977	13,843,562	738,723	1,085,143	944,750
1978	21,243,378	868,963	788,319	1,714,508
1979	10,977,908	888,276	1,073,885	1,284,635
1980	14,478,306	1,651,187	1,120,416	1,136,685
1981	18,967,933	849,692	1,079,625	1,406,846
1982	24,247,128	1,359,130	1,493,429	2,137,646
1983	37,497,400	1,195,700	1,568,900	1,985,100
1984	25,821,700	4,046,900	1,203,900	1,920,200
1985	50,988,200	3,266,800	1,849,100	2,539,500

Table A4. Estimates of biomass of pink, chum, sockeye, and coho salmon landed in the commercial fisheries of Southeast Alaska, 1911-85.

	Catch in Pounds			
Year	Pink	Chum	Sockeye	Coho
1911			14,617,562	
1912		47,263,574	16,853,210	
1913		20,862,380	11,907,127	
1914		47,181,093	19,703,719	
1915	137,364,310	29,881,014	15,962,784	
1916	100,608,656	40,638,230	12,080,337	
1917	166,395,891	61,587,093	13,963,414	
1918	157,479,788	77,361,821	14,984,770	12,749,032
1919	116,171,033	91,160,711	17,084,958	13,680,092
1920	76,418,391	66,744,155	15,028,100	8,142,843
1921	33,352,933	15,396,388	7,587,730	8,520,741
1922	103,365,013	33,820,488	9,502,219	10,639,566
1923	169,761,106	34,410,704	11,908,351	10,376,641
1924	126,423,110	63,519,649	12,870,744	8,772,678
1925	128,688,375	67,275,288	9,585,914	8,754,258
1926	162,771,616	49,464,990	11,578,756	11,406,588
1927	44,428,747	18,073,881	7,786,796	13,542,561
1928	161,836,320	46,048,498	7,147,944	18,908,445
1929	116,452,988	23,380,792	10,930,192	11,972,249
1930	174,604,760	23,118,365	14,764,171	15,944,028
1931	152,627,203	22,010,691	9,871,129	10,593,817
1932	104,032,959	45,885,462	9,244,717	11,671,132
1933	111,378,706	33,668,025	5,415,641	10,827,423
1934	197,740,699	31,375,741	7,198,047	17,609,762
1935	165,839,641	42,955,792	10,679,180	14,089,212
1936	220,534,369	62,990,247	14,545,889	15,908,230
1937	161,552,824	41,486,578	11,166,602	10,328,209
1938	142,322,678	38,921,540	13,066,192	19,794,677
1939	111,207,565	24,010,405	13,659,953	9,356,769
1940	109,870,342	38,881,711	8,363,870	18,713,557
1941	274,343,472	25,995,703	9,175,747	21,170,752
1942	132,330,890	47,979,120	7,745,884	19,594,948
1943	78,642,216	56,879,851	5,684,084	14,814,323
1944	83,008,120	58,631,059	9,504,202	14,219,024
1945	79,589,906	27,785,382	9,094,837	27,340,949
1946	75,987,225	34,472,356	4,528,116	18,818,726

- Continued -

Table A4. (p. 2 of 2).

Year	Catch in Pounds			
	Pink	Chum	Sockeye	Coho
1947	51,827,811	21,664,670	3,723,758	12,973,162
1948	52,198,459	32,975,711	2,643,076	18,294,083
1949	160,284,337	20,560,454	2,634,186	17,789,853
1950	40,940,133	41,198,465	3,313,791	14,155,447
1951	93,025,496	38,877,575	4,685,532	25,470,213
1952	44,841,901	42,893,360	4,953,648	12,663,379
1953	26,404,349	33,869,748	8,419,180	10,672,597
1954	39,774,781	47,874,282	7,553,266	17,634,420
1955	41,206,762	14,224,920	3,714,030	9,867,305
1956	47,985,726	24,482,645	5,398,700	8,554,655
1957	30,704,430	30,344,866	5,476,917	10,376,722
1958	52,621,152	30,113,121	5,980,742	8,587,697
1959	35,768,567	12,634,185	4,526,439	8,604,222
1960	10,455,381	10,216,266	3,235,037	5,292,095
1961	63,922,100	23,118,200	4,754,700	7,799,600
1962	45,746,850	19,470,180	4,858,160	9,585,580
1963	70,054,650	12,649,630	3,905,800	11,304,790
1964	71,505,320	19,535,900	5,500,390	12,834,340
1965	42,431,740	15,033,440	6,620,440	13,624,730
1966	89,927,949	28,149,153	7,168,012	10,800,282
1967	14,000,630	17,379,956	6,120,708	7,796,034
1968	82,781,816	28,822,422	5,815,425	12,190,448
1969	20,453,437	5,165,036	4,707,164	4,354,377
1970	41,442,236	20,483,428	4,248,930	5,822,974
1971	34,414,077	16,095,008	3,967,147	7,136,576
1972	38,468,017	26,840,276	5,698,331	10,585,584
1973	23,423,770	17,748,456	7,023,806	6,161,160
1974	19,270,771	17,005,676	4,657,449	9,412,587
1975	15,552,250	6,430,914	1,522,036	3,083,857
1976	23,350,853	11,009,767	3,930,665	6,354,875
1977	67,890,028	7,509,417	7,555,140	8,247,515
1978	67,767,148	8,102,540	5,217,022	11,482,258
1979	43,255,000	8,452,000	6,846,000	8,854,000
1980	56,315,000	16,452,000	7,056,000	8,052,000
1981	80,784,000	8,380,000	6,629,000	10,525,000
1982	79,455,000	13,377,000	10,040,000	15,459,000
1983	117,133,000	10,695,000	9,549,000	13,672,000
1984	88,450,000	38,303,000	7,482,000	16,241,000
1985	165,499,000	29,559,000	11,512,000	20,384,000

APPENDIX B
CONSTRUCTION OF AIR TEMPERATURE SERIES

Southern Southeast Alaska

Hamilton (1965) examined the air temperature record for Ketchikan for the years 1913 through 1962, and reported that station moves in 1929 and 1938 showed no indication of displacing the temperature record. In September 1975, the elevation at which temperature was measured in Ketchikan changed (from 20 feet to 90 feet), and in January 1978, the measurement station was relocated.

A significant seasonal displacement of air temperatures measured in Ketchikan is apparent when the measurement elevation changed in 1975. Quantifying the effect of the 1978 station relocation is complicated by the sharp increase of mean annual air temperatures between about 1971 and 1978, and by the 42 months or so of missing data following the 1978 move. Thus, a long-term record of temperatures for southern Southeast Alaska was constructed by combining early temperature records for Ketchikan with data for Annette Island (about 15 miles south of Ketchikan), where temperature was measured consistently between 1949 and 1986.

Differences in temperature between Ketchikan and Annette Island were calibrated to permit combining the two records. This was done by calculating differences between daily temperatures measured in Ketchikan and Annette from September 1949 to September 1975. Seasonal differences are apparent between the two locations, so mean monthly differences in temperature (Table B1) were used to produce a long-term record which could be updated by using Annette Island temperatures.

The record of monthly mean temperatures in Ketchikan is relatively complete for the period December 1910 through September 1949 (Table B2). Missing monthly mean temperatures in Ketchikan during this period were estimated from monthly mean temperatures at the Fortmann Salmon Hatchery, with seasonal corrections clearly being necessary (Table B3). Because sample sizes are small, corrections for measurement location (by month) were estimated from temperature differences which had been smoothed using the 4253H-twice algorithm (Velleman 1980).

At least two errors were discovered in the (NCDC) electronic data obtained for Ketchikan: March 1960 temperatures were erroneous, and the 28th (or 27th) of each month from January 1971 through November 1971 was incorrectly entered as 26.5^{o} F.

Table B1. Mean and median differences[a] between daily Ketchikan air temperatures (NCDC station 4590) and daily Annette air temperatures (NCDC station 352), September 1949 through August 1975.

Month	Mean Temperature Difference	Number of Observations	Median Temperature Difference
January	0.56	806	0.50
February	0.84	734	0.50
March	0.41	806	0.50
April	0.46	780	0.25
May	0.34	806	0.50
June	0.33	780	0.00
July	0.36	806	0.50
August	0.26	775	0.50
September	0.16	780	0.00
October	0.11	806	0.00
November	0.42	780	0.50
December	0.60	806	0.50

[a] Temperature at Ketchikan - temperature at Annette, in degrees F.

Table B2. Months when data from correlation stations were used to complete temperature records for Ketchikan, Juneau, and Sitka, Alaska.

Ketchikan	Correlation Station
1911 Jul-Dec	Fortmann Salmon Hatchery
1912 Jan-Apr	Fortmann Salmon Hatchery
1913 Apr	Fortmann Salmon Hatchery
1917 May	Fortmann Salmon Hatchery
1919 Dec	Fortmann Salmon Hatchery
1921 Jul-Aug	Fortmann Salmon Hatchery
Juneau Airport	**Correlation Station**
1941 Oct	Downtown Juneau
1943 Apr-Jun	Downtown Juneau
1976 May	Downtown Juneau
1985 Sept-Nov	Downtown Juneau
1986 Apr-May	Downtown Juneau
Sitka	**Correlation Station**
1936 Feb	Downtown Juneau
1959 Jul	Sitka Airport
1978 Apr	Sitka Airport

Table B3. Mean differences[a] between monthly mean Fortmann Salmon Hatchery and Ketchikan air temperatures, January 1911 through December 1922, and mean temperature differences after smoothing with the 4253H-twice algorithm.

Month	Mean Temperature Difference	Number of Observations	Smoothed Temperature Difference
January	-3.9	11	-4.09
February	-3.5	11	-3.20
March	-1.6	11	-2.00
April	-0.9	10	-0.76
May	0.1	11	0.25
June	1.2	12	0.83
July	1.3	10	0.97
August	0.7	10	0.81
September	0.3	11	0.31
October	-0.5	11	-0.46
November	-1.1	11	-1.36
December	-2.2	10	-2.20

[a] Temperature at Fortmann - temperature at Ketchikan, in degrees F.

Juneau

Juneau air temperature has been regularly reported from a variety of locations and elevations in the downtown area since 1907, and from the Juneau Airport since 1941. Hamilton (1965) reported that four relocations of the Downtown Juneau (DTJ) measuring stations before 1962 had no obvious effect on the data. Since Hamilton's analyses, significant relocations (according to NCDC "type of station change" codes) took place in July 1965 and in April 1975. The airport location has not changed substantially since 1941, however, and airport records are much more complete than DTJ records in recent years. These factors led me to construct a long-term series for Juneau, using DTJ temperatures between 1910 and 1940 and airport temperature after 1940, and adjusting for differences due to measurement location. Daily temperature differences between the Juneau Airport (NCDC station 4100) and DTJ (NCDC station 4092) were calculated to estimate the relationship between the two locations (Table B4). The need for seasonal adjustment is apparent from the skewed distribution of monthly differences, especially in winter. Therefore, median differences were used to adjust DTJ temperatures to the airport location.

Measurements of temperature at the Juneau Airport were not made in 10 months after 1940 (Table B2). Airport temperatures in these months were thus estimated from median temperature differences between downtown Juneau and the airport, from 1941 to 1986 (Table B5).

Sitka

Two time series of air temperature can be constructed for Sitka. The longest record dates from 1843 (Juday 1984) and is called Sitka Magnetic (since October 1948) or Sitka Magnetic Observatory (since December 1969). According to Hamilton (1965) the Sitka magnetic station was relocated in 1930, 1941, and 1942, but only the move in April 1942 resulted in a noticeable effect. The location of the station has not changed since Hamilton's analyses. The second record for Sitka is from an airport for which NCDC electronic records begin in September 1949. NCDC station history records indicate the airport station was not moved substantially since 1949.

A temperature record for Sitka from December 1910 to December 1986 was constructed by completing the NCDC electronic daily temperature record for the Sitka Magnetic stations from May 1917 to December 1986 and then appending U.S. Weather Bureau mean monthly temperatures for Sitka between December 1910 and May 1917. Three months of missing data (Table B2) were estimated from correlation stations;

Table B4. Mean and median differences[a] between daily Juneau Airport air temperatures (NCDC station 4100) and daily downtown Juneau air temperatures (NCDC station 4092), September 1949 through June 1965.

Month	Mean Temperature Difference	Number of Observations	Median Temperature Difference
January	-3.69	460	-3.00
February	-3.13	449	-2.50
March	-2.85	494	-2.50
April	-2.45	466	-2.00
May	-2.33	494	-2.00
June	-2.46	419	-2.00
July	-2.38	463	-2.00
August	-2.30	461	-2.00
September	-2.53	471	-2.00
October	-2.09	494	-2.00
November	-2.66	473	-2.50
December	-3.14	493	-2.50

[a] Temperature at airport - temperature downtown, in degrees F.

Table B5. Mean and median differences[a] between daily Juneau Airport air temperatures (NCDC station 4100) and daily downtown Juneau air temperatures (NCDC station 4094), April 1975 through December 1986.

Month	Mean Temperature Difference	Number of Observations	Median Temperature Difference
January	-2.35	306	-1.50
February	-2.19	304	-2.00
March	-1.41	310	-1.00
April	-0.69	300	-0.50
May	-0.02	290	0.00
June	-0.22	300	0.00
July	-0.23	340	0.00
August	-0.50	335	-0.50
September	-0.98	295	-1.00
October	-0.84	307	-1.00
November	-1.95	270	-1.50
December	-2.62	330	-2.00

[a] Temperature at airport - temperature downtown, in degrees F.

temperatures during February 1936 were estimated from Juneau temperatures and July 1959 and April 1978 temperatures were estimated from temperatures measured at the Sitka Airport. In addition, 66 scattered missing daily observations, 38 of which occurred since 1978, were estimated by linear interpolation.

Missing values of air temperature for the Sitka Magnetic station were estimated from temperature at the Sitka Airport, as described above (for Juneau), with median values used for the estimations (Table B6). The effect of moving the Sitka measurement site in April 1942 was estimated by subtracting monthly mean Sitka temperatures from Downtown Juneau air temperatures for 5 years before and 5 years after the move, and then taking the differences between these averages (Table B7). Since a monthly trend in the differences is not evident, the mean of 1.1° F was subtracted from the early station data. This value is in close agreement with Juday (1984), who reported adjustments of 1.0° and 1.1°, respectively, for summer and mean annual temperatures. Mean monthly Sitka temperature in February 1936 was estimated by the average difference between Juneau and Sitka temperatures in February from 1931 to 1941. The estimate for February is 4.2° F (colder in Juneau), which is nearly the same as the correction for February (between 1937 and 1942) shown in Table B7.

Table B6. Mean and median differences[a] between daily Sitka Magnetic air temperatures (NCDC station 8503) and daily Sitka Airport air temperatures (NCDC station 8494), September 1949 through December 1986.

Month	Mean Temperature Difference	Number of Observations	Median Temperature Difference
January	-2.92	1144	-2.50
February	-1.90	1044	-2.00
March	-1.53	1141	-1.50
April	-1.38	1079	-1.50
May	-1.47	1111	-1.50
June	-1.43	1106	-1.50
July	-1.47	1113	-1.50
August	-1.51	1140	-1.50
September	-1.57	1139	-1.50
October	-1.57	1170	-1.50
November	-2.21	1135	-2.00
December	-2.67	1175	-2.50

[a] Temperature at Sitka Magnetic - temperature at airport, in degrees F.

Table B7. Differences between Juneau and Sitka mean monthly air temperatures for 5 years before ($\bar{x}_b$) and 5 years after ($\bar{x}_a$) the April 1942 move of the Sitka measurement station. Tabled values are temperature differences in degrees F. The mean difference across months ($\bar{x}_b$-$\bar{x}_a$) provides an adjustment for change in location of the Sitka measurement station.

Year	Month 1	2	3	4	5	6	7	8	9	10	11	12
1937				-0.6	1.2	2.6	0.9	0.4	-0.3	-1.5	-2.9	-5.9
1938	-3.5	-5.9	-0.7	0.0	1.6	2.1	2.1	1.8	-1.2	-0.3	-3.1	-3.7
1939	-2.7	-5.5	-3.9	-0.8	1.0	3.6	0.7	-0.3	-1.3	-3.1	-2.8	-1.0
1940	-6.3	-4.8	-3.6	-0.4	0.4	0.1	0.7	-2.0	-1.9	-2.4	-4.9	-3.6
1941	-4.8	-3.3	-4.2	-0.6	1.3	1.5	0.2	0.4	-1.9	-3.2	-4.5	-6.2
1942	-4.0	-4.1	-2.8									
$\bar{x}_b$	-4.26	-4.72	-3.04	-0.48	1.10	1.96	0.92	0.05	-1.32	-2.10	-3.64	-4.08
SD	1.20	0.94	1.26	0.26	0.43	1.17	0.61	1.23	0.57	1.06	0.86	1.86
1942				-0.8	1.1	3.0	1.4	0.9	-1.3	-1.3	-3.1	-7.6
1943	-4.5	-5.5	-1.2	0.6	2.5	4.0	1.9	0.8	-0.2	0.3	-0.3	-1.0
1944	-0.9	-1.9	-0.7	1.9	2.7	5.7	2.2	1.8	1.1	-0.9	-2.6	0.1
1945	-2.9	-3.6	0.2	-1.0	2.4	1.8	-0.3	1.2	-2.2	-1.5	-5.2	-1.9
1946	-1.5	-2.2	-0.4	-1.0	1.4	4.5	0.3	-0.2	0.1	-1.9	-1.4	-5.9
1947	-3.2	-4.8	-0.9									
$\bar{x}_a$	-2.62	-3.60	-0.60	-0.05	2.02	3.79	1.11	0.89	-0.48	-1.07	-2.50	-3.27
SD	1.30	1.41	0.45	1.18	0.64	1.34	0.93	0.63	1.16	0.73	1.67	2.98
$\bar{x}_b$-$\bar{x}_a$	-1.64	-1.11	-2.43	-0.42	-0.92	-1.83	-0.19	-0.84	-0.84	-1.03	-1.14	-0.81

Mean of ($\bar{x}_b$-$\bar{x}_a$) = -1.10

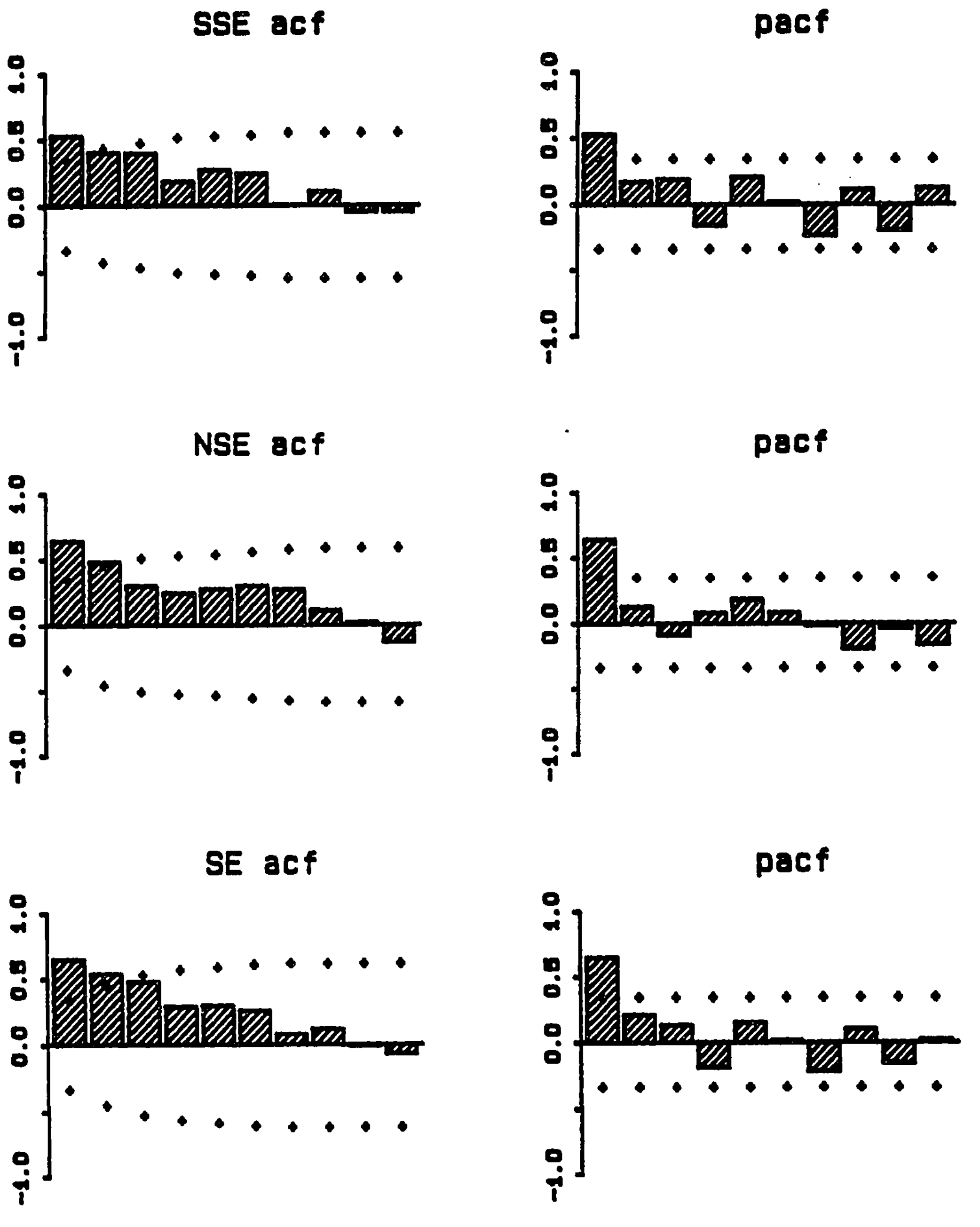

Figure C1. Autocorrelation function (acf) and partial autocorrelation function (pacf) of southern (SSE), northern (NSE), and Southeast Alaska (SE) commercial harvests of even-year pink salmon.

Southern Even-yr Pink

p	q= 0	1	2	3	4	5	6
0	X	X	X	O	O	O	O
1	O	O	O	O	O	O	O
2	X	O	O	O	O	O	O
3	X	O	O	O	O	O	O
4	X	O	O	O	O	O	O
5	O	O	O	O	O	O	O
6	O	O	O	O	O	O	O
7	X	X	O	O	O	O	O

Southern Odd-yr Pink

p	q= 0	1	2	3	4	5	6
0	X	O	X	O	O	O	O
1	O	O	O	O	O	O	O
2	X	X	O	O	O	O	O
3	O	O	O	O	O	O	O
4	O	O	O	O	O	O	O
5	X	O	O	O	O	O	O
6	X	O	O	O	O	O	O
7	O	O	O	O	O	O	O

Northern Even-yr Pink

p	q= 0	1	2	3	4	5	6
0	X	X	O	O	O	O	O
1	O	O	O	O	O	O	O
2	X	O	O	O	O	O	O
3	X	O	O	O	O	O	O
4	O	O	O	O	O	O	O
5	X	O	O	O	O	O	O
6	O	O	O	O	O	O	O
7	O	O	O	O	O	O	O

Northern Odd-yr Pink

p	q= 0	1	2	3	4	5	6
0	X	O	O	O	O	O	O
1	O	O	O	O	O	O	O
2	O	O	O	O	O	O	O
3	O	O	O	O	O	O	O
4	O	O	O	O	O	O	O
5	X	O	O	O	O	O	O
6	X	O	O	O	O	O	O
7	X	X	O	O	O	O	O

Southeast Even-yr Pink

p	q= 0	1	2	3	4	5	6
0	X	X	X	O	O	O	O
1	O	O	O	O	O	O	O
2	X	O	O	O	O	O	O
3	X	O	O	O	O	O	O
4	X	O	O	O	O	O	O
5	O	O	O	O	O	O	O
6	O	O	O	O	O	O	O
7	X	X	O	O	O	O	O

Southeast Odd-yr Pink

p	q= 0	1	2	3	4	5	6
0	X	O	O	O	O	O	O
1	O	O	O	O	O	O	O
2	O	X	O	O	O	O	O
3	O	X	O	O	O	O	O
4	O	O	O	O	O	O	O
5	O	O	O	O	O	O	O
6	O	O	X	O	O	O	O
7	O	O	O	O	O	O	O

Figure C2. ESACF Tables for pink salmon catches in Southeast Alaska fishing areas. Square root transformations were applied to all series except that log transformations were applied to the odd-year pink salmon series in northern Southeast and Southeast Alaska. The symbol X denotes a nonzero value and O denotes 0.

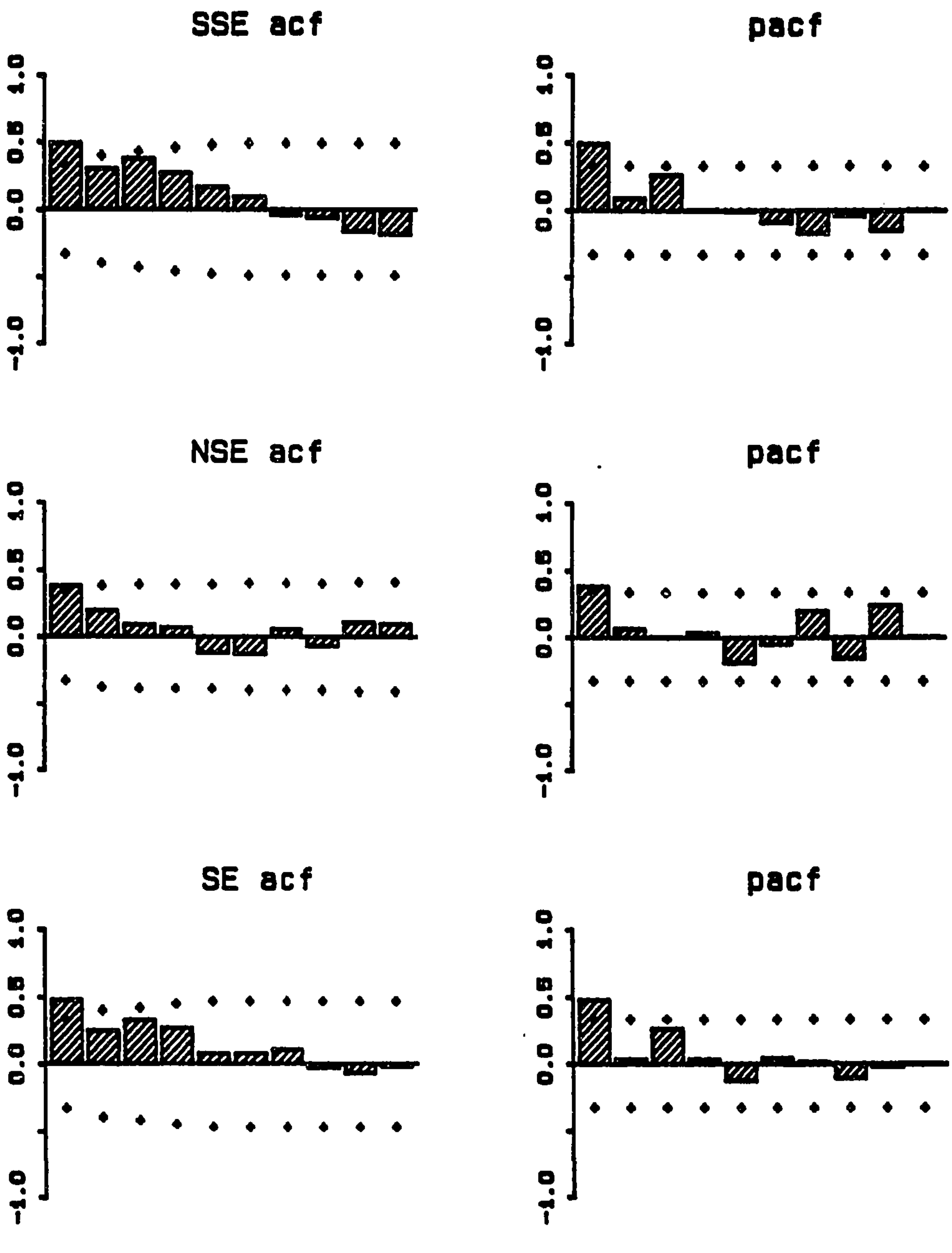

Figure C3. Autocorrelation function (acf) and partial autocorrelation function (pacf) of southern (SSE), northern (NSE), and Southeast Alaska (SE) commercial harvests of odd-year pink salmon.

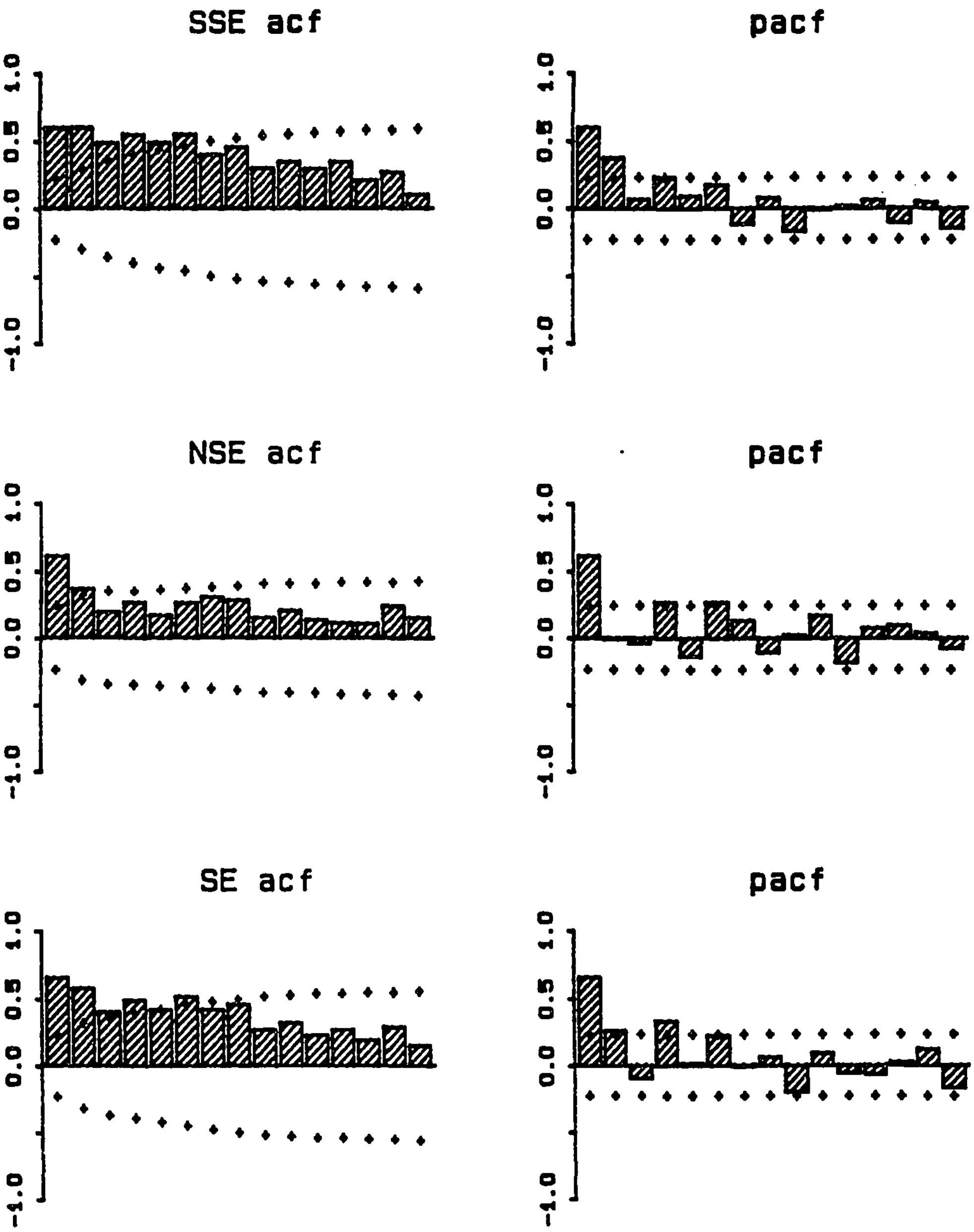

Figure C4. Autocorrelation function (acf) and partial autocorrelation function (pacf) of southern (SSE), northern (NSE), and Southeast Alaska (SE) commercial harvests of chum salmon.

Southern Chum

p	q= 0	1	2	3	4	5	6
0	X	X	X	X	X	X	X
1	X	O	O	O	O	O	O
2	O	X	O	O	O	O	O
3	X	X	O	O	O	O	O
4	X	X	O	O	O	O	O
5	X	X	X	O	O	O	O
6	X	O	O	O	O	O	O
7	X	O	O	O	O	O	O

Northern Chum

p	q= 0	1	2	3	4	5	6
0	X	X	O	X	O	X	X
1	O	O	O	X	O	O	O
2	X	O	O	O	O	O	O
3	O	O	O	O	O	O	O
4	X	X	O	O	X	O	O
5	X	O	X	O	O	O	O
6	X	X	O	O	O	X	O
7	X	O	O	O	O	X	O

Southeast Chum

p	q= 0	1	2	3	4	5	6
0	X	X	X	X	X	X	X
1	X	O	X	O	O	O	O
2	X	O	X	O	O	O	O
3	X	X	O	O	O	O	O
4	O	X	O	O	O	O	O
5	O	X	O	O	O	O	O
6	O	X	O	O	X	O	O
7	O	O	O	O	X	O	O

Figure C5. ESACF Tables for **chum salmon** catches in Southeast Alaska fishing areas. Square root transformations were applied to all series. The symbol X denotes a nonzero value and O denotes 0.

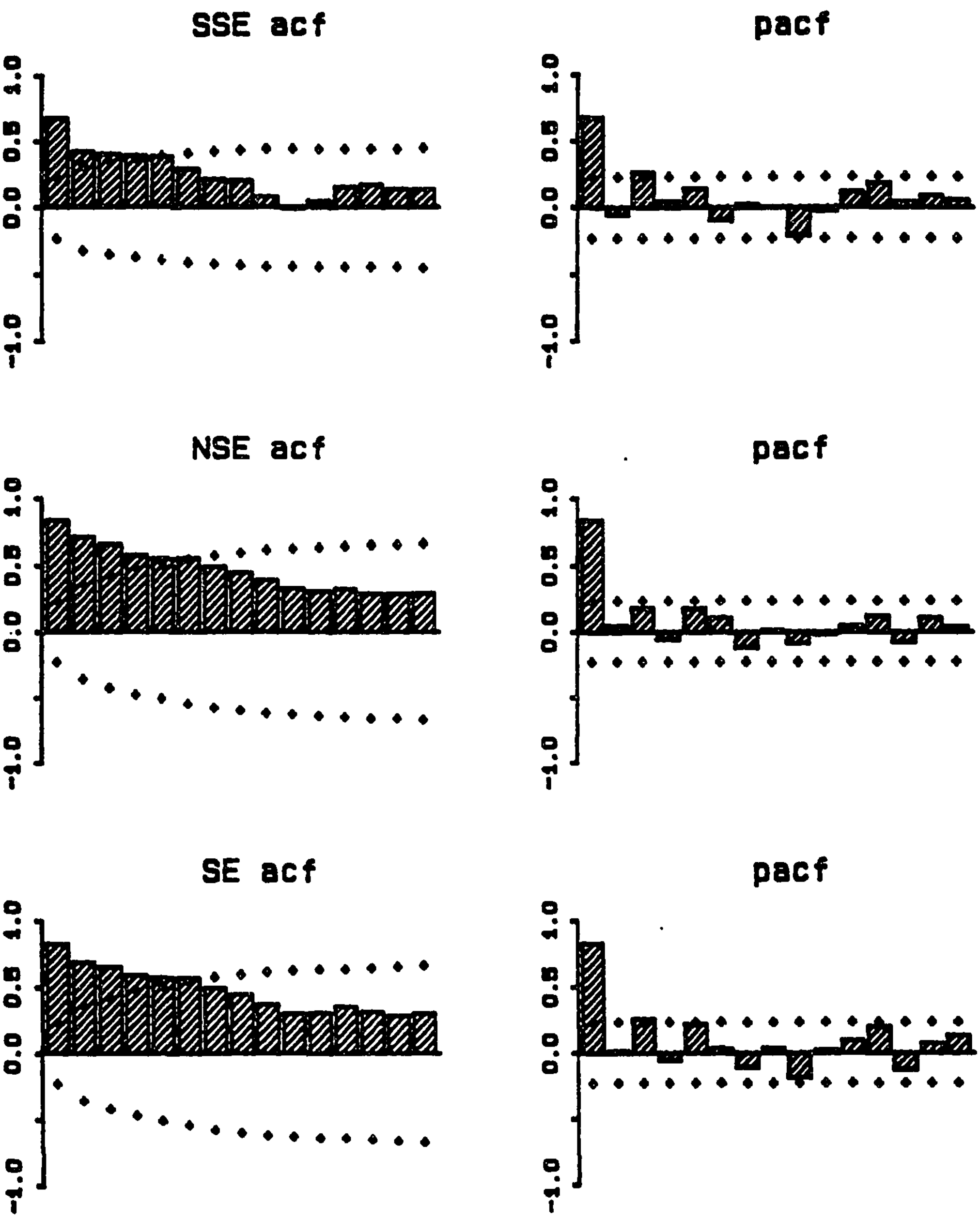

Figure C6. Autocorrelation function (acf) and partial autocorrelation function (pacf) of southern (SSE), northern (NSE), and Southeast Alaska (SE) commercial harvests of sockeye salmon.

	Southern Sockeye						
p q=	0	1	2	3	4	5	6
0	X	X	X	X	X	X	O
1	O	X	O	O	O	O	O
2	X	X	O	O	O	O	O
3	O	X	O	O	O	O	O
4	O	X	X	O	O	O	O
5	X	O	O	O	O	O	O
6	X	O	O	O	X	O	O
7	X	O	O	O	O	O	O

	Northern Sockeye						
p q=	0	1	2	3	4	5	6
0	X	X	X	X	X	X	X
1	O	O	O	O	O	O	O
2	X	O	O	O	O	O	O
3	X	X	O	O	O	O	O
4	O	X	O	O	O	O	O
5	X	O	X	X	O	O	O
6	X	O	O	O	O	O	O
7	X	X	O	O	O	O	O

	Southeast Sockeye						
p q=	0	1	2	3	4	5	6
0	X	X	X	X	X	X	X
1	O	X	O	O	O	O	O
2	O	X	O	O	O	O	O
3	O	X	O	O	O	O	O
4	O	X	O	O	O	O	O
5	X	X	O	X	O	O	O
6	X	O	O	X	O	O	O
7	X	X	O	X	O	O	O

Figure C7. ESACF Tables for sockeye salmon catches in Southeast Alaska fishing areas. Square root transformations were applied to all series. The symbol X denotes a nonzero value and O denotes 0.

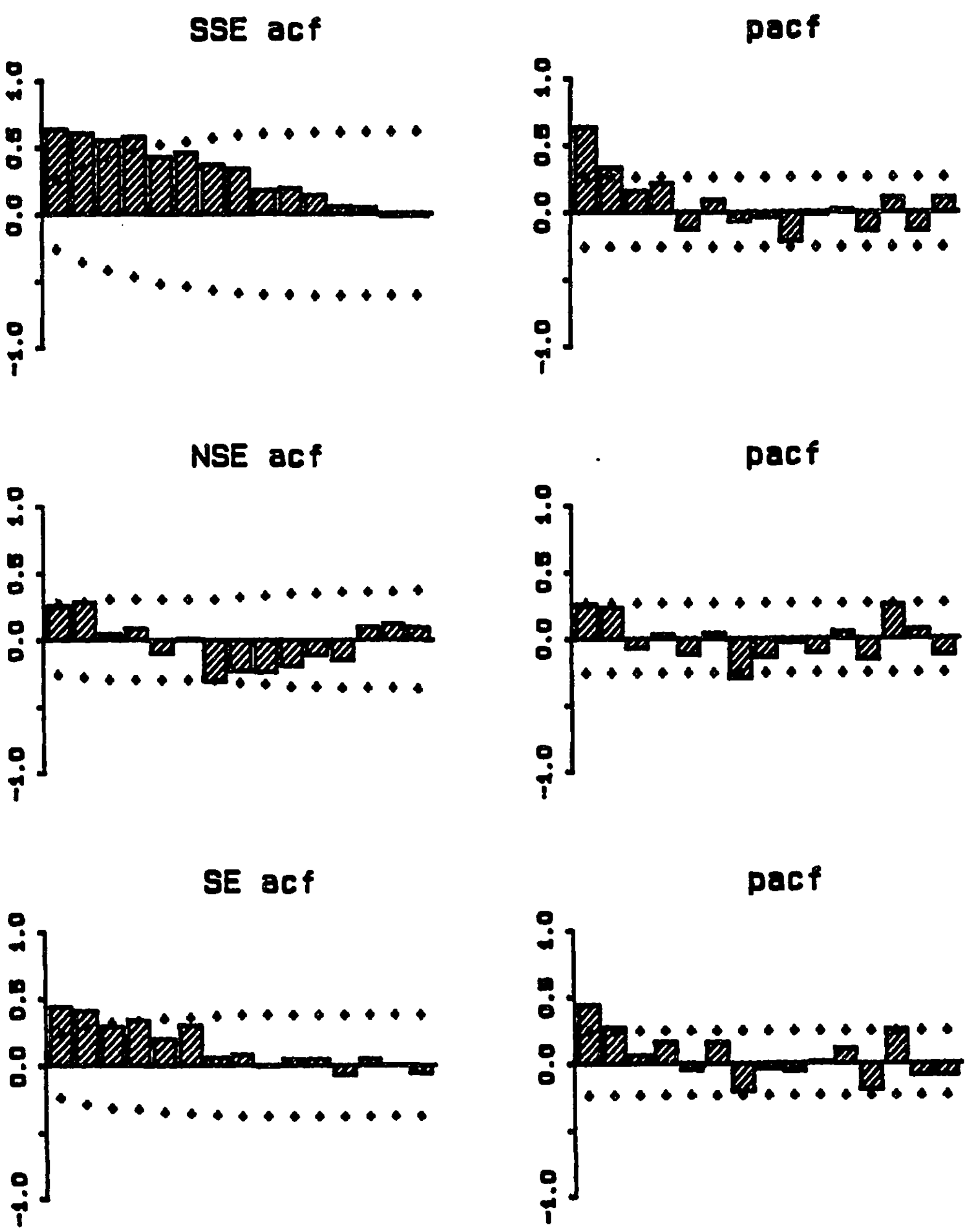

Figure C8. Autocorrelation function (acf) and partial autocorrelation function (pacf) of southern (SSE), northern (NSE), and Southeast Alaska (SE) commercial harvests of coho salmon.

Southern Coho

p	q= 0	1	2	3	4	5	6
0	X	X	X	X	X	X	X
1	X	O	O	O	O	O	O
2	X	O	O	O	O	O	O
3	X	O	O	O	O	O	O
4	X	O	O	O	O	O	O
5	X	X	O	O	O	O	O
6	X	O	O	O	O	O	O
7	X	O	O	O	O	O	O

Northern Coho

p	q= 0	1	2	3	4	5	6
0	O	X	O	O	O	O	X
1	X	O	O	O	O	O	O
2	O	O	O	O	O	O	O
3	X	O	O	O	O	O	O
4	X	X	O	O	O	O	O
5	O	X	O	O	O	O	O
6	O	X	O	O	O	X	O
7	X	O	O	O	X	X	O

Southeast Coho

p	q= 0	1	2	3	4	5	6
0	X	X	X	X	O	X	O
1	X	O	O	O	O	O	O
2	O	X	O	O	O	O	O
3	X	X	O	O	O	O	O
4	X	X	O	O	O	O	O
5	X	O	O	O	O	O	O
6	X	O	X	X	O	O	O
7	O	O	O	O	O	X	O

Figure C9. ESACF Tables for coho salmon catches in Southeast Alaska fishing areas. The southern series was transformed to its square root and the log transformation was applied to the northern and Southeast Alaska series. The symbol X denotes a nonzero value and O denotes 0.

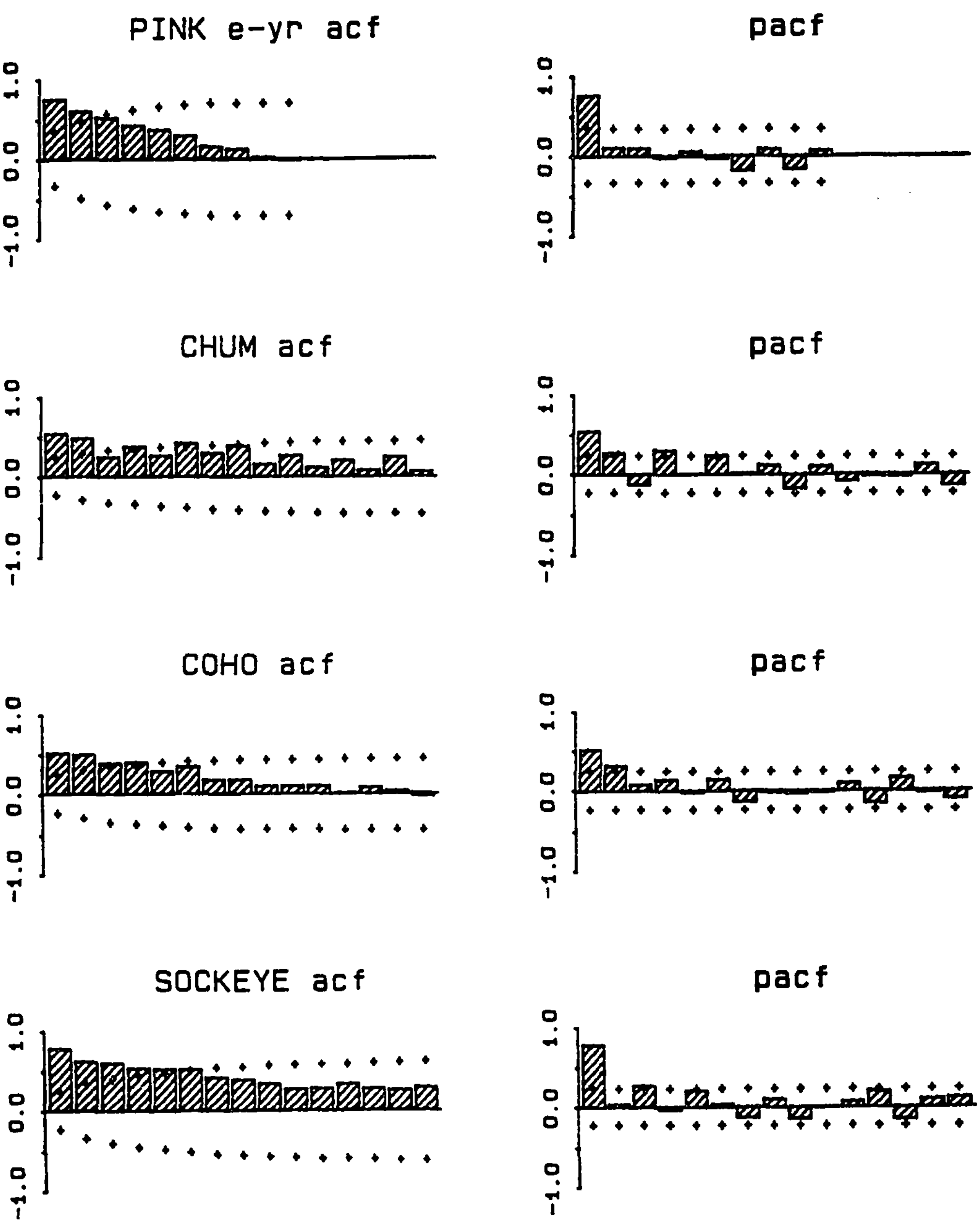

Figure C10. Autocorrelation function (acf) and partial autocorrelation function (pacf) of Southeast Alaska (SE) commercial salmon **harvest biomasses (pounds).**

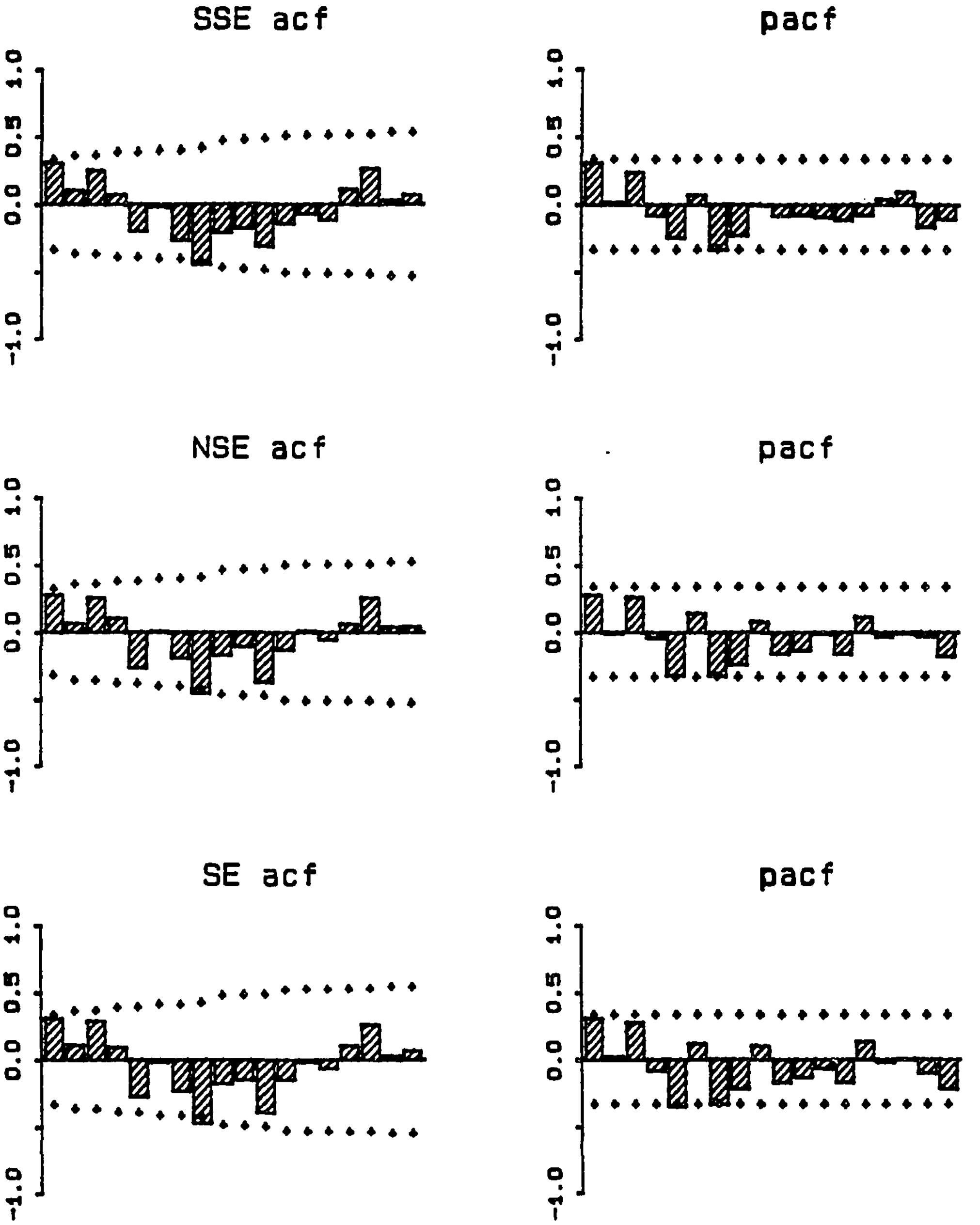

Figure C11. Autocorrelation function (acf) and partial autocorrelation function (pacf) of low (7-day minimum) winter air temperatures in southern (SSE), northern (NSE), and Southeast Alaska.

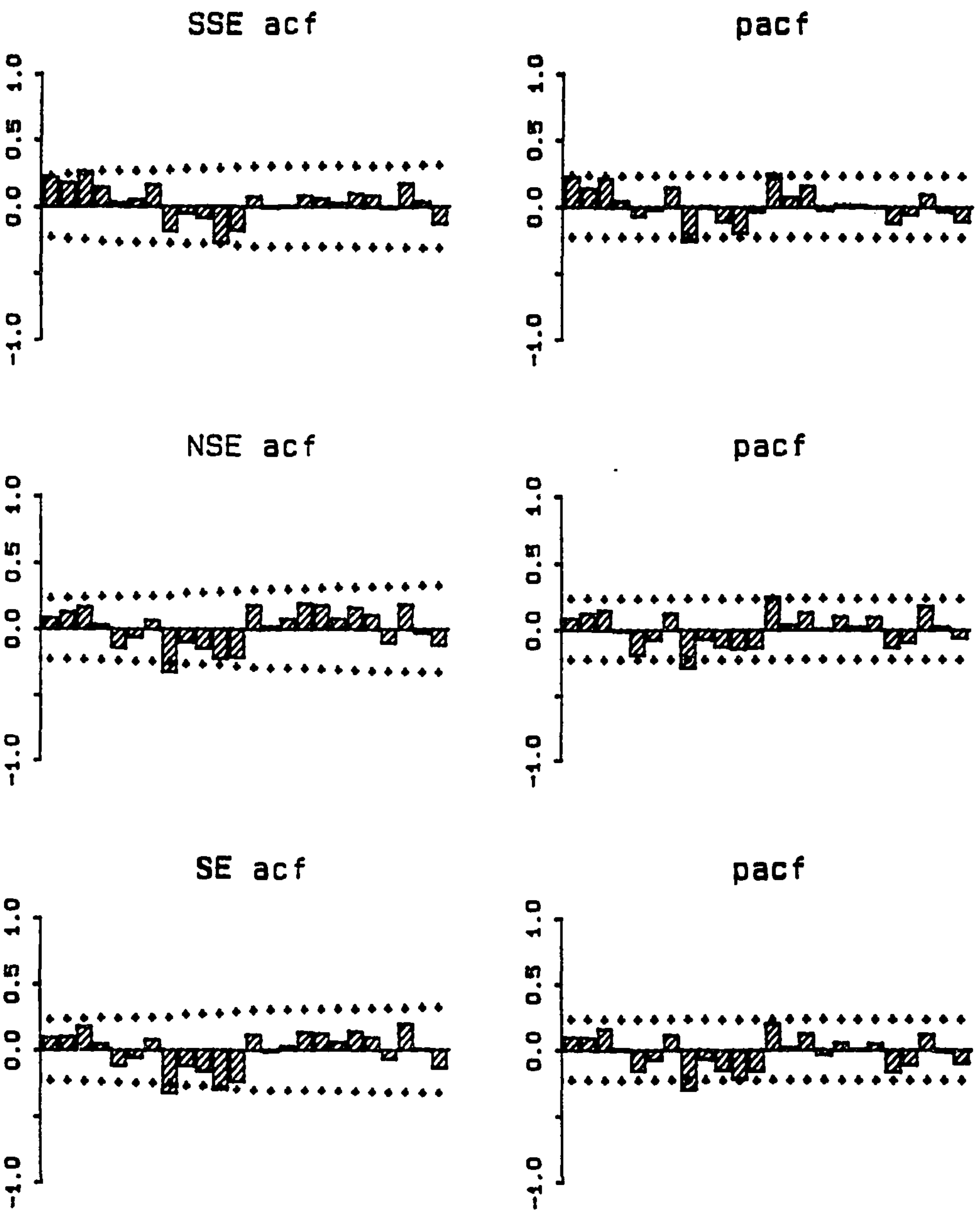

Figure C12. Autocorrelation function (acf) and partial autocorrelation function (pacf) of mean (December through February) winter air temperatures in southern (SSE), northern (NSE), and Southeast Alaska.

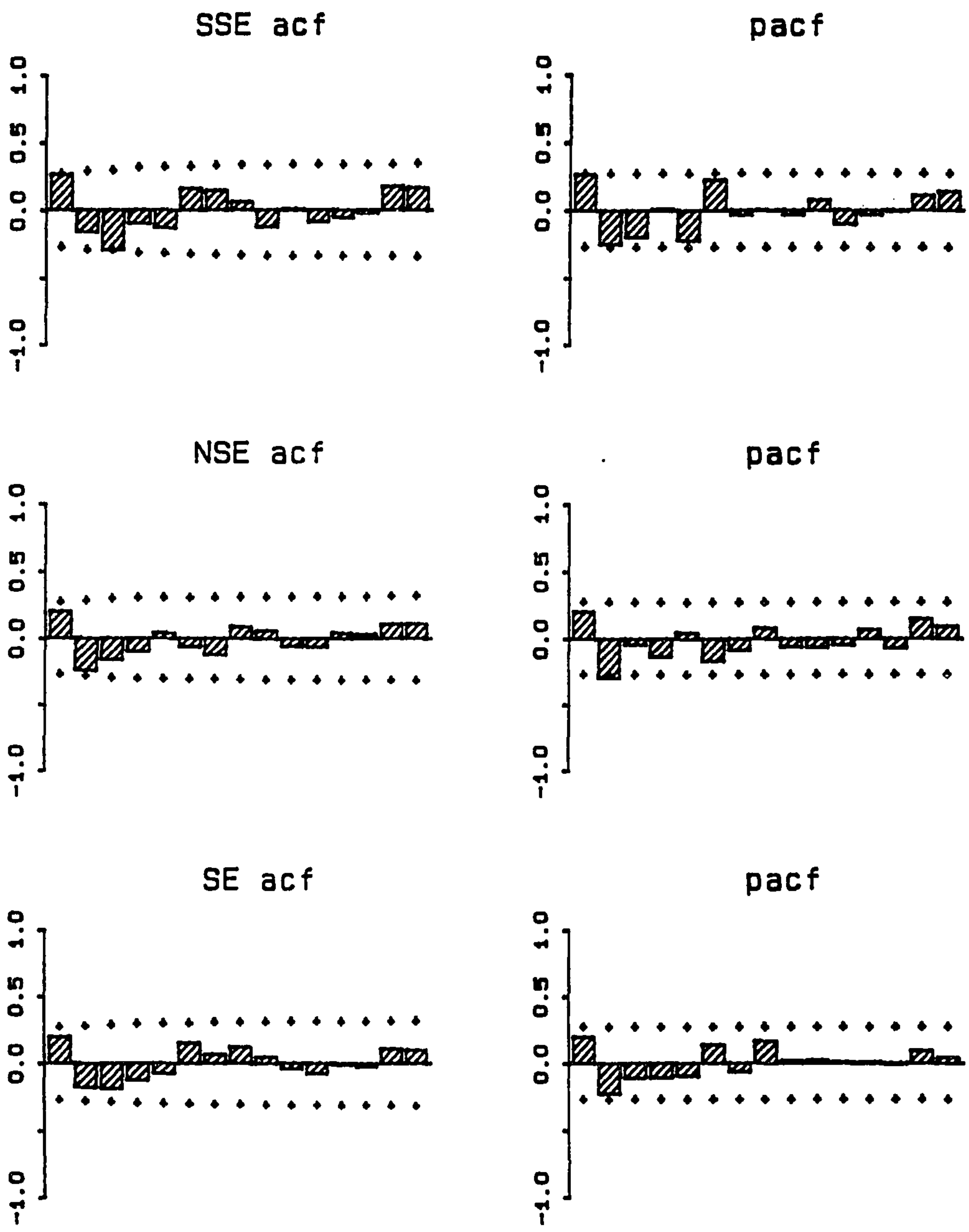

Figure C13. Autocorrelation function (acf) and partial autocorrelation function (pacf) of seasonal (fall spawning) freshwater discharges in southern (SSE), northern (NSE), and Southeast Alaska.

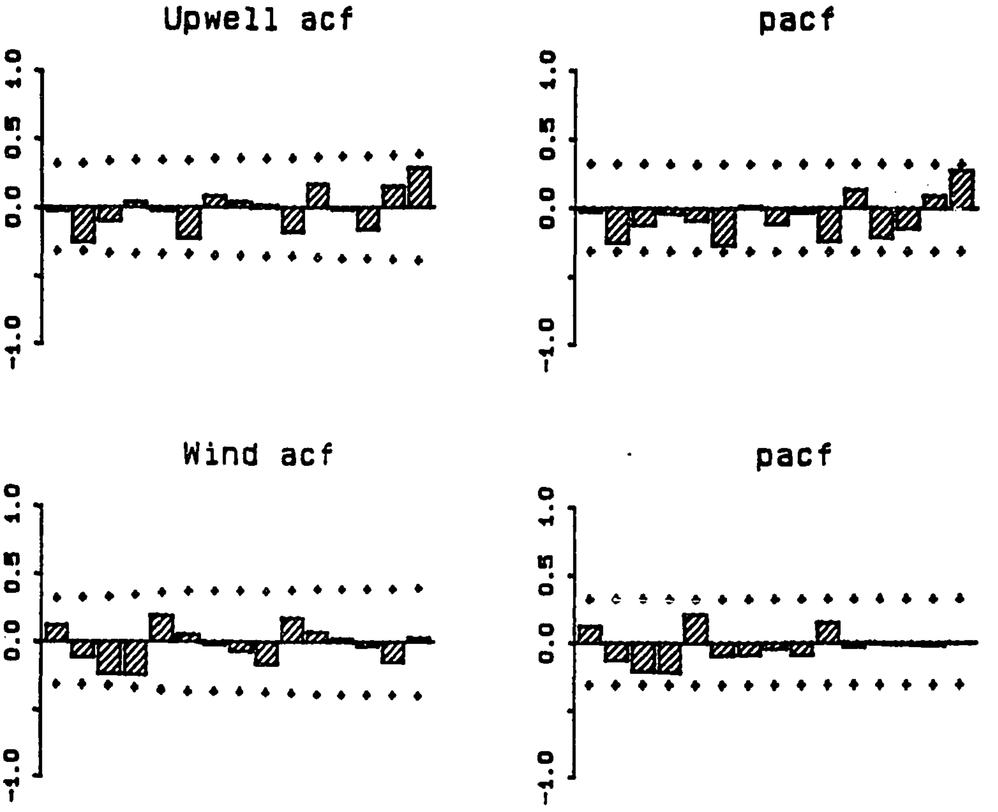

Figure C14. Autocorrelation function (acf) and partial autocorrelation function (pacf) of mean June and July upwelling off Southeast Alaska, and August through October wind speed near Seward, Alaska.

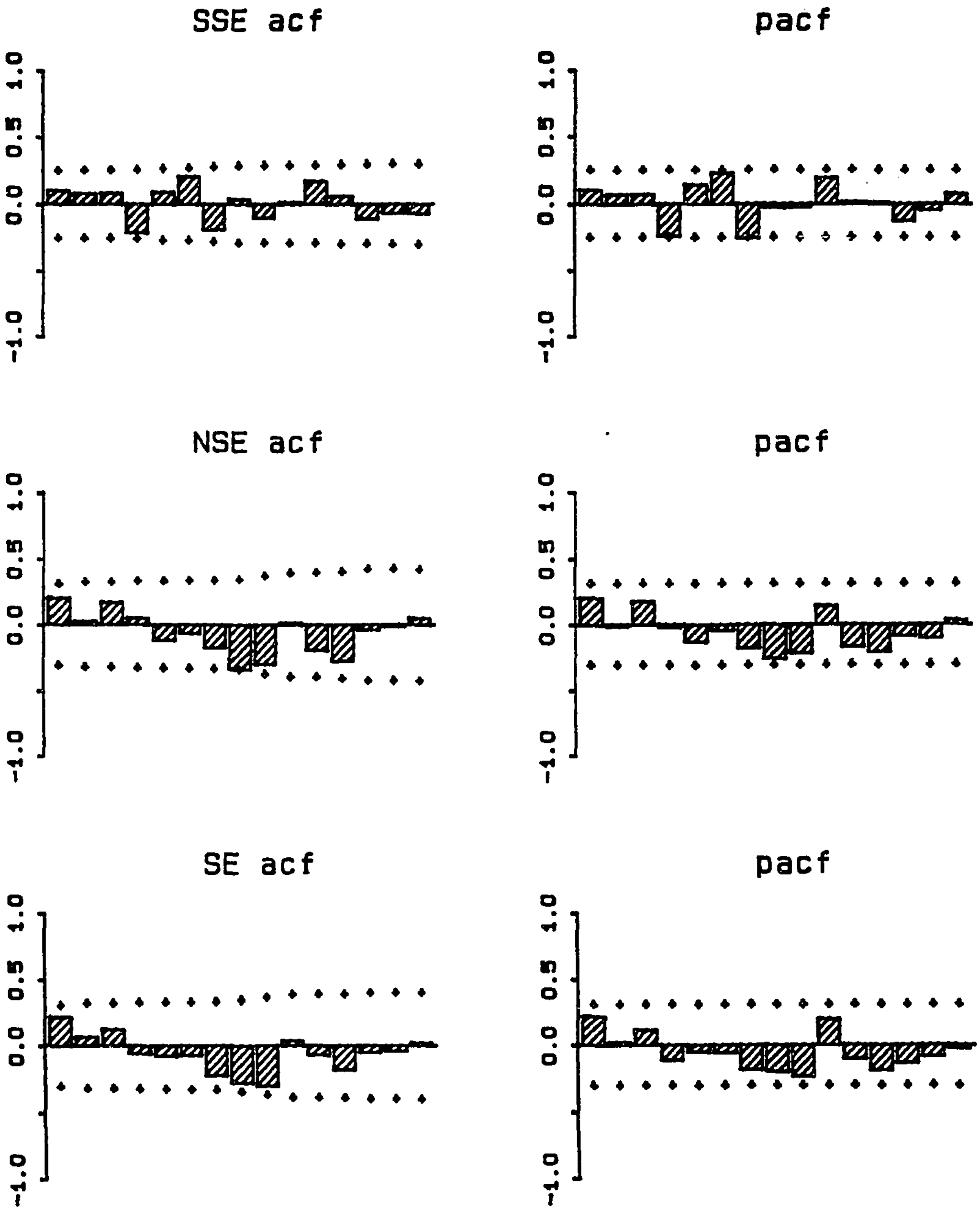

Figure C15. Autocorrelation function (acf) and partial autocorrelation function (pacf) of mean May and June SST in southern (SSE), northern (NSE), and Southeast Alaska.

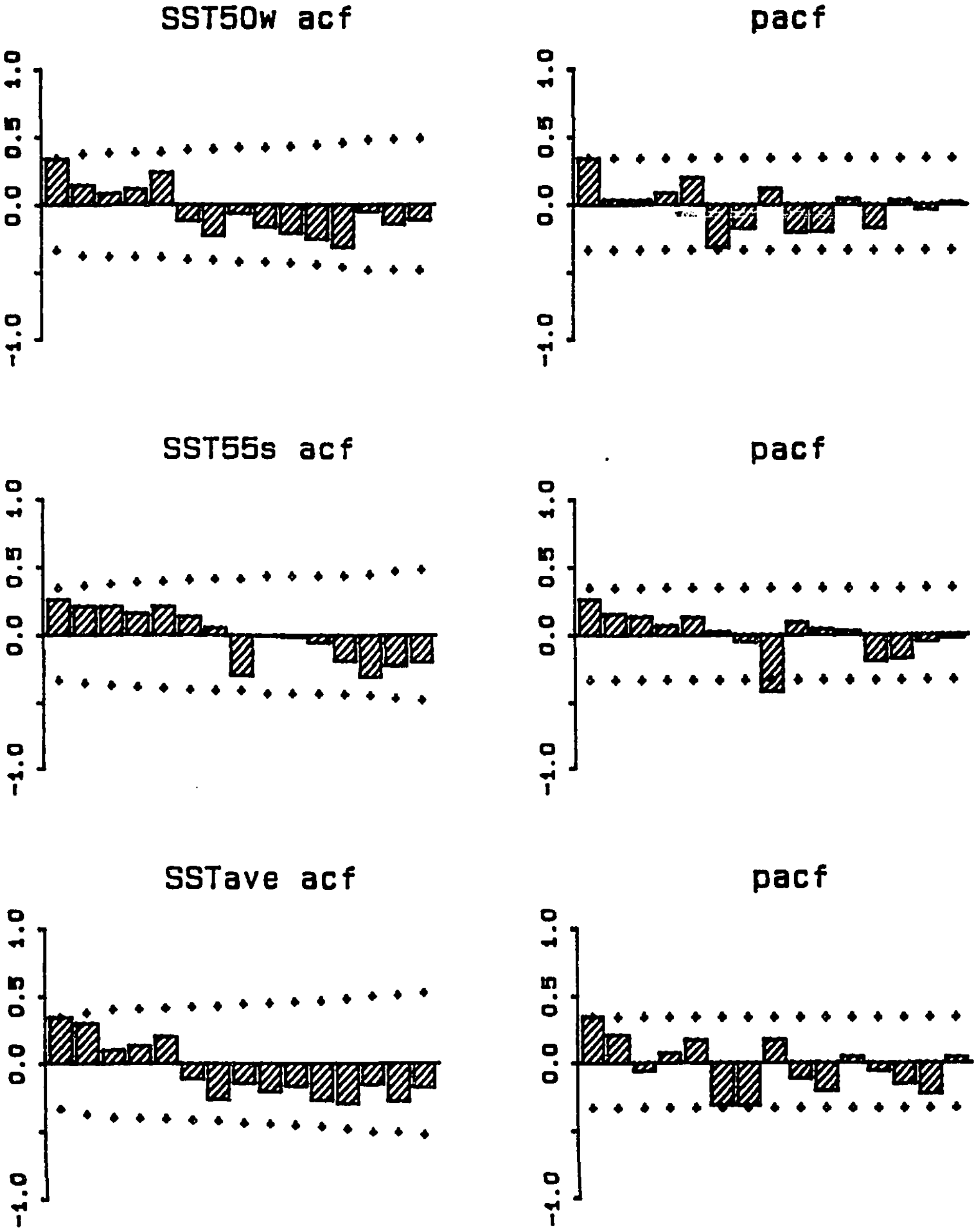

Figure C16. Autocorrelation function (acf) and partial autocorrelation function (pacf) of mean January through April SST at 50°N (SST50w), July through October SST at 55°N (SST55s), and November through June SST at 45°N, 50°N, and 55°N (SSTave).

Table D1. Cross-correlations between square root transformed **combined even- and odd-year pink salmon** catches in southern, northern, and Southeast Alaska, and environmental data 0 to 3 years before the catch.

		Lag in Years Before Catch[a]			
SSE vs.	n	0	1	2	3
SSEdis	55*	-.017	-.019	.149	**.225**
SSEcold	36	-.023	**.118**	.061	.055
SSEwint	69	.012	.034	**.083**	.070
SSEsst	64	**.246u**	.218	.167	.233
SEupw	40	.045	**-.131**	-.106	-.025
Nwind	40	**.178**	.027	-.079	.101
SST55s	35	.023	**.096**	-.053	.017
SSTave	35*	**.194**	.109	-.000	.001
NSE vs.	n	0	1	2	3
NSEdis	55	-.119	.131	**.264**	.091
NSEcold	36	.096	.125	**.206**	.123
NSEwint	71	.169	.178	**.250u**	.159
NSEsst	42	.047	**.438u**	.309	.214
SEupw	40	.037	**.136**	-.132	.116
Nwind	40	.179	**-.229**	.011	.103
SST55s	35	.084	**.301**	.284	.179
SSTave	35	.240	**.373u**	.281	.300
SE vs.	n	0	1	2	3
SEdis	55	-.051	.053	.211	**.227**
SEcold	36	.089	**.231**	.179	.147
SEwint	71	.099	.126	**.177**	.145
SEsst	42	.085	**.363u**	.315u	.311
SEupw	40	.055	-.062	**-.147**	.029
Nwind	40	**.204**	-.056	-.037	.118
SST55s	35	.058	**.192**	.083	.081
SSTave	35*	.239	**.248**	.110	.145

[a] Lags expected to be important (Table 3.2) are underlined and the highest correlation between variables is bold. Significant correlations (P≤0.05) are indicated with a u. An asterisk after n indicates both series were autocorrelated (2 SE).

Table D2. Correlations between square root transformed **even-year pink salmon** catches in southern, northern, and Southeast Alaska, and environmental data 0 to 3 years before the catch.

		Lag in Years Before Catch[a]			
SSE vs.	n	0	1	2	3
SSEdis	26	**-.151**	.131	<u>-.069</u>	.131
SSEcold	16	-.298	<u>.309</u>	-.234	.118
SSEwint	34	-.050	<u>.058</u>	.033	**.156**
SSEsst	30*	**.529u**	<u>.074</u>	.192	.222
SEupw	18	**.282**	<u>.085</u>	-.044	-.138
Nwind	18	-.127	<u>.207</u>	.110	-.048
SST55s	16	-.097	<u>.236</u>	**-.512u**	-.060
SSTave	16	<u>.074</u>	.184	**-.384**	.062
NSE vs.	**n**	**0**	**1**	**2**	**3**
NSEdis	26	-.102	.202	<u>**.213**</u>	.084
NSEcold	16	**-.372**	<u>-.016</u>	-.297	-.151
NSEwint	35	.104	<u>.172</u>	.164	**.188**
NSEsst	19	.177	<u>**.350**</u>	.078	.042
SEupw	18	.112	<u>**.684u**</u>	.135	-.066
Nwind	18	-.001	<u>**-.397**</u>	-.052	.049
SST55s	16	-.088	<u>**.360**</u>	-.111	.284
SSTave	16	<u>.136</u>	.195	.144	**.220**
SE vs.	**n**	**0**	**1**	**2**	**3**
SEdis	26	-.185	.215	<u>-.117</u>	**.236**
SEcold	16	**-.431**	<u>.286</u>	-.209	.037
SEwint	35	.021	<u>.167</u>	.128	**.221**
SEsst	19	.255	<u>**.339**</u>	.032	.272
SEupw	18	.253	<u>**.322**</u>	.026	-.152
Nwind	18	**-.098**	<u>-.011</u>	.047	-.007
SST55s	16	-.125	<u>.326</u>	**-.415**	.068
SSTave	16	<u>.110</u>	.210	**-.222**	.154

[a] Lags expected to be important (Table 3.2) are underlined and the highest correlation between variables is bold. Significant correlations (P≤0.05) are indicated with a **u**. An asterisk after n indicates both series were autocorrelated (2 SE).

Table D3. Correlations between square root transformed **odd-year pink salmon** catches in southern, northern, and Southeast Alaska, and environmental data 0 to 3 years before the catch.

		Lag in Years Before Catch[a]			
SSE vs.	n	0	1	2	3
SSEdis	26	.045	-.106	.294	**.382**
SSEcold	17	.204	.057	**.251**	-.028
SSEwint	36	.035	-.026	.041	**-.045**
SSEsst	31	.044	**.361u**	.244	.246
SEupw	19	-.079	**-.225**	-.164	.040
Nwind	19	**.246**	-.112	-.241	.220
SST55s	16	.090	-.030	**.220**	.040
SSTave	16	**.438**	.031	.285	-.053
NSE vs.	n	0	1	2	3
NSEdis	26	-.177	.017	**.341**	.102
NSEcold	17	.276	.467	.472	**.539u**
NSEwint	36	.239	.201	**.367u**	.204
NSEsst	20	-.028	**.603u**	.517u	.433
SEupw	19	-.010	-.275	**-.403**	.242
Nwind	19	**.336**	-.090	.141	.166
SST55s	16	.168	.376	**.562u**	.152
SSTave	16	.363	**.566u**	.363	.444
SE vs.	n	0	1	2	3
SEdis	26	.007	-.112	**.433u**	.274
SEcold	17	.379	.306	**.397**	.240
SEwint	36	.170	.094	**.217**	.101
SEsst	20	-.059	.424	**.513u**	.401
SEupw	19	-.055	-.260	**-.284**	.131
Nwind	19	**.295**	-.107	-.105	.224
SST55s	16	.150	.124	**.386**	.100
SSTave	16	**.453**	.259	.352	.160

[a] Lags expected to be important (Table 3.2) are underlined and the highest correlation between variables is bold. Significant correlations (P≤0.05) are indicated with a **u**. An asterisk after n indicates both series were autocorrelated (2 SE).

Table D4. Cross-correlations between square root transformed **chum salmon** catches in southern, northern, and Southeast Alaska, and environmental data 0 to 5 years before the catch.

		Lag in Years Before Catch[a]					
SSE vs.	n	0	1	2	3	4	5
SSEdis	55*	.193	.052	-.002	.009	**.289u**	.236
SSEcold	36	-.145	.039	**-.299**	-.069	.005	.057
SSEwint	74*	**-.201**	-.197	-.198	-.186	-.027	-.037
SSEsst	64	.151	.210	.146	.224	**.302u**	.282u
SEupw	40	-.103	-.051	-.113	**-.238**	-.027	.063
Nwind	40	.096	.165	**.253**	.096	-.058	-.028
SST55s	35	.203	.243	-.068	.254	.256	**.326**
SST50w	35	.064	.010	-.142	.011	.112	**.137**
NSE vs.	n	0	1	2	3	4	5
NSEdis	55	.097	.020	-.009	.106	**.303u**	.278u
NSEcold	36	-.204	**-.384u**	-.336	-.039	-.107	-.018
NSEwint	68	-.015	-.058	.046	**.138**	.094	.083
NSEsst	42	-.148	-.101	-.163	.181	**.315**	.144
SEupw	40	-.010	-.044	.021	**.197**	.004	-.019
Nwind	40	.150	.097	.065	-.161	**-.182**	.131
SST55s	35	.209	.040	.016	.291	**.380u**	.374u
SST50w	35*	.001	-.164	**-.232**	-.031	.232	.143
SE vs.	n	0	1	2	3	4	5
SEdis	55	.141	.042	.017	.039	.256	**.328u**
SEcold	36	-.250	-.220	**-.342u**	-.021	-.049	.057
SEwint	74	-.085	**-.138**	-.061	.013	.090	.068
SEsst	42	-.102	-.036	-.080	.246	**.355u**	.207
SEupw	40	**-.058**	-.053	-.055	-.017	-.013	.009
Nwind	40	.147	.155	**.193**	-.036	-.123	.071
SST55s	35	.227	.143	-.022	.310	.370u	**.394u**
SST50w	35*	.016	-.111	**-.219**	-.017	.205	.160

[a] Lags expected to be important (Table 3.2) are underlined and the highest correlation between variables is bold. Significant correlations (P≤0.05) are indicated with a **u**. An asterisk after n indicates both series were autocorrelated (2 SE).

Table D5. Cross-correlations between square root transformed **coho salmon** catches in southern, northern, and Southeast Alaska, and environmental data 0 to 5 years before the catch.

		Lag in Years Before Catch[a]					
SSE vs.	n	0	1	2	3	4	5
SEcdis	55	.110	.092	.260	.240	<u>.286</u>u	**.346u**
SSEcold	36	**-.251**	.030	.062	<u>.023</u>	.236	.229
SSEwint	57	.007	.128	.189	<u>.149</u>	**.299u**	.211
Lowsdis	55	-.081	.003	<u>.014</u>	<u>.150</u>	**.170**	.149
SSEsst	57	.171	<u>.285</u>u	.252	.337u	**.410u**	.358u
SEupw	40	.010	-<u>.125</u>	-.091	-.129	**-.150**	-.019
Nwind	40	**.292**	<u>.103</u>	.096	.116	-.111	-.049
SST55s	35	.122	<u>.113</u>	.012	.023	**.226**	.202
SSTave	35	<u>.127</u>	.117	.073	-.003	**.203**	.059
NSE vs.	**n**	**0**	**1**	**2**	**3**	**4**	**5**
SEcdis	55	-.211	**-.399u**	-.043	.140	<u>.050</u>	.136
NSEcold	36	-.087	-.049	-.020	-<u>.017</u>	.111	**.299**
NSEwint	58	**-.147**	.002	-.111	<u>.042</u>	.063	.041
Lowsdis	55	-.165	**-.255**	-<u>.158</u>	<u>.085</u>	.017	-.125
NSEsst	42	-.179	<u>.243</u>	-.050	.170	**.343u**	.294
SEupw	40	**.151**	<u>.059</u>	-.020	-.041	-.123	-.047
Nwind	40	-.077	**-<u>.153</u>**	-.030	.071	-.131	.044
SST55s	35	**.269**	<u>.053</u>	.098	.043	.179	.168
SSTave	35*	<u>.008</u>	.102	.049	.015	.112	**.196**
SE vs.	**n**	**0**	**1**	**2**	**3**	**4**	**5**
SEcdis	55	.000	-.110	.204	.261	<u>.263</u>	**.335u**
SEcold	36	-.156	.026	.039	<u>.027</u>	.216	**.337**
SEwint	68	.021	.213	.175	<u>.161</u>	**.324u**	.153
Lowsdis	55	-.130	-.132	-<u>.065</u>	**<u>.188</u>**	.139	.072
SEsst	42	-.045	<u>.304</u>	.093	.226	**.387u**	.312
SEupw	40	.086	-<u>.041</u>	-.071	-.095	**-.145**	-.057
Nwind	40	**.156**	-<u>.024</u>	.045	.099	-.146	-.013
SST55s	35	**.247**	<u>.138</u>	.094	.054	.237	.216
SSTave	35*	<u>.084</u>	.150	.089	.020	**.180**	.166

[a] Lags expected to be important (Table 3.2) are underlined & the highest correlation between variables is bold. Significant correlations (P≤0.05) are indicated with a **u**. Asterisks indicate the series are autocorrelated (2 SE).

Table D6. Cross-correlations between square root transformed **sockeye salmon** catches in southern, northern, and Southeast Alaska, and environmental data 0 to 6 years before the catch.

		Lag in Years Before Catch[a]						
SSE vs.	n	0	1	2	3	4	5	6
SSEdis	55*	.169	.041	-.011	.061	.172	**.275**	.209
SSEcold	36	.126	.075	-.027	-.058	**.280**	.218	.209
SSEwint	75*	.111	-.066	-.134	**-.156**	-.010	-.042	-.147
SSEsst	64	**.286u**	.102	.112	.139	.172	.161	.038
SEupw	40	.146	**.185**	.126	-.091	-.186	-.017	-.017
Nwind	40	-.025	-.233	-.045	-.183	**-.258**	-.127	-.027
SST55s	35	**.313**	.078	.058	-.027	.120	.055	-.117
SST50w	35*	**.510u**	.449u	.225	.076	.257	.059	.100
NSE vs.	n	0	1	2	3	4	5	6
NSEdis	55	.121	.211	.143	-.020	.030	.087	**.232**
NSEcold	36	.003	-.119	-.030	-.110	-.149	.140	**.333**
NSEwint	75	.096	.065	.089	.101	.084	.084	**.133**
NSEsst	42	.133	.107	-.046	.071	.120	**.191**	.110
SEupw	40	-.182	.094	**.313**	.140	-.118	.035	.085
Nwind	40	.134	-.030	-.122	**-.238**	-.160	.035	.048
SST55s	35	.314	.161	.381u	.338	.403u	**.466u**	.244
SST50w	35*	.013	-.006	-.009	.171	.151	.085	**.368u**
SE vs.	n	0	1	2	3	4	5	6
SEdis	55	.185	.146	.107	-.004	.038	**.237**	.232
SEcold	36	.114	-.027	-.028	-.050	.165	.240	**.333**
SEwint	75	.029	**-.078**	-.075	-.054	-.009	-.019	-.027
SEsst	42	.183	.098	-.024	.036	**.201**	.099	-.007
SEupw	40	.027	.141	**.225**	.030	-.166	-.017	.013
Nwind	40	.061	-.218	-.139	**-.271**	-.268	-.040	-.003
SST55s	35	**.326**	.096	.200	.118	.227	.179	-.046
SST50w	35*	**.361u**	.321	.166	.138	.260	.052	.238

[a] Lags expected to be important (Table 3.2) are underlined and the highest correlation between variables is bold. Significant correlations (P≤0.05) are indicated with a **u**. An asterisk after n indicates both series were autocorrelated (2 SE).

Table E1. Correlation coefficients for square root transformed and untransformed salmon catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska.

SSE: 1929-1985	$Pink^{0.5}$	$Chum^{0.5}$	$Sock^{0.5}$	$Coho^{0.5}$
$Pink^{0.5}$	1.000			
$Chum^{0.5}$	0.509	1.000		
$Sock^{0.5}$	0.570	0.356	1.000	
$Coho^{0.5}$	0.760	0.678	0.441	1.000
	Pink	Chum	Sock	Coho
Pink	1.000			
Chum	0.418	1.000		
Sock	0.580	0.372	1.000	
Coho	0.683	0.617	0.419	1.000
NSE: 1928-1985	$Pink^{0.5}$	$Chum^{0.5}$	$Sock^{0.5}$	$Coho^{0.5}$
$Pink^{0.5}$	1.000			
$Chum^{0.5}$	0.389	1.000		
$Sock^{0.5}$	0.560	0.553	1.000	
$Coho^{0.5}$	0.252	0.029	-0.013	1.000
	Pink	Chum	Sock	Coho
Pink	1.000			
Chum	0.316	1.000		
Sock	0.518	0.465	1.000	
Coho	0.205	0.016	-0.069	1.000
SE: 1918-1985	$Pink^{0.5}$	$Chum^{0.5}$	$Sock^{0.5}$	$Coho^{0.5}$
$Pink^{0.5}$	1.000			
$Chum^{0.5}$	0.494	1.000		
$Sock^{0.5}$	0.594	0.622	1.000	
$Coho^{0.5}$	0.651	0.363	0.266	1.000
	Pink	Chum	Sock	Coho
Pink	1.000			
Chum	0.424	1.000		
Sock	0.560	0.660	1.000	
Coho	0.608	0.267	0.202	1.000

Table F1. Forecasts, actual catches, and relative errors of forecasts from vector AR(4) models of square root transformed **pink salmon** catches in southern (SSE), northern (NSE) and Southeast (SE) Alaska fishing areas. Catch in numbers/10^7.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.510	1.115	1.953	1.347	-17.2	17.2
82	0.659	1.325	2.220	1.292	2.6	2.6
83	0.745	1.435	2.351	3.142	-54.3	54.3
84	0.807	1.553	2.540	2.090	-25.7	25.7
85	1.841	2.897	4.191	3.047	-4.9	4.9
86	1.597	2.579	3.796			
				medians	-17.2	17.2
				means	-19.9	21.0

	Northern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.067	0.331	0.796	0.536	-38.3	38.3
82	0.066	0.328	0.790	1.132	-71.0	71.0
83	0.227	0.642	1.267	0.605	6.1	6.1
84	0.266	0.699	1.338	0.490	42.6	42.6
85	0.160	0.517	1.078	2.050	-74.8	74.8
86	0.312	0.806	1.532			
				medians	-38.3	42.6
				means	-27.1	46.6

	Southeast Alaska Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.728	1.533	2.634	1.897	-19.2	19.2
82	0.813	1.649	2.777	2.425	-32.0	32.0
83	1.257	2.256	3.546	3.750	-39.8	39.8
84	1.323	2.356	3.685	2.582	-8.8	8.8
85	1.652	2.776	4.189	5.099	-45.6	45.6
86	2.040	3.305	4.874			
				medians	-32.0	32.0
				means	-29.1	29.1

Table F2. Forecasts, actual catches, and relative errors of forecasts from vector AR(4) models of square root transformed **chum salmon** catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^6.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.556	0.949	1.446	0.352	169.9	169.9
82	0.589	1.008	1.539	0.840	20.0	20.0
83	0.420	0.778	1.245	0.514	51.5	51.5
84	0.969	1.484	2.107	1.831	-19.0	19.0
85	1.155	1.708	2.370	1.301	31.3	31.3
86	1.199	1.758	2.424			
				medians	31.3	31.3
				means	50.7	58.3

	Northern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.709	1.069	1.504	0.487	119.4	119.4
82	0.363	0.642	0.999	0.513	25.1	25.1
83	0.632	0.984	1.414	0.671	46.7	46.7
84	1.803	2.372	3.018	2.184	8.6	8.6
85	1.834	2.403	3.048	1.954	23.0	23.0
86	1.321	1.809	2.374			
				medians	25.1	25.1
				means	45.5	44.5

	Southeast Alaska Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.524	1.098	1.882	0.850	29.3	29.3
82	0.557	1.143	1.937	1.359	-15.9	15.9
83	1.102	1.877	2.856	1.196	57.0	57.0
84	1.325	2.164	3.207	4.047	-46.5	46.5
85	2.605	3.775	5.162	3.267	15.6	15.6
86	2.035	3.073	4.324			
				medians	15.6	29.3
				means	7.9	32.8

Table F3. Forecasts, actual catches, and relative errors of forecasts from vector AR(4) models of square root transformed **coho salmon** catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^5 except SE is catch in numbers/10^6.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	4.054	6.729	10.078	6.408	5.0	5.0
82	4.404	7.150	10.559	8.216	-13.0	13.0
83	5.326	8.283	11.891	8.662	-4.4	4.4
84	6.222	9.357	13.131	6.657	40.6	40.6
85	8.297	11.868	16.077	11.984	-1.0	1.0
86	8.602	12.194	16.411			
				medians	-1.0	5.0
				means	5.5	12.8

	Northern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	4.130	6.854	10.265	6.010	14.0	14.0
82	3.890	6.518	9.820	10.786	-39.6	39.6
83	4.397	7.209	10.712	10.180	-29.2	29.2
84	4.923	7.885	11.542	10.832	-27.2	27.2
85	5.259	8.306	12.047	11.476	-27.6	27.6
86	5.234	8.283	12.028			
				medians	-27.6	27.6
				means	-21.9	27.5

	Southeast Alaska Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.813	1.259	1.802	1.407	-10.5	10.5
82	0.961	1.435	2.004	2.138	-32.9	32.9
83	1.001	1.491	2.077	1.985	-24.9	24.9
84	1.108	1.623	2.236	1.920	-15.5	15.5
85	1.218	1.753	2.384	2.540	-31.0	31.0
86	1.309	1.869	2.527			
				median	-24.9	24.9
				means	-22.9	22.9

Table F4. Forecasts, actual catches, and relative errors of forecasts from vector AR(4) models of square root transformed sockeye salmon catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^5 except SE is catch in numbers/10^6.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	4.729	7.113	9.981	7.200	-1.2	1.2
82	4.694	7.049	9.881	8.421	-16.3	16.3
83	6.023	8.644	11.736	9.437	-8.4	8.4
84	6.153	8.773	11.858	6.476	35.5	35.5
85	5.502	7.986	10.931	11.117	-28.2	28.2
86	6.944	9.728	12.980			
				medians	-8.4	16.3
				means	-3.7	17.9

	Northern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	1.498	2.496	3.748	2.099	19.0	19.0
82	1.863	2.948	4.281	4.389	-32.8	32.8
83	3.524	4.986	6.701	4.723	5.6	5.6
84	3.916	5.438	7.210	4.548	19.6	19.6
85	3.122	4.482	6.087	5.040	-11.1	11.1
86	4.703	6.325	8.187			
				medians	5.6	19.0
				means	0.0	17.6

	Southeast Alaska Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.629	0.962	1.366	1.080	-10.9	10.9
82	0.701	1.049	1.466	1.493	-29.8	29.8
83	1.047	1.467	1.957	1.569	-6.5	6.5
84	0.958	1.357	1.826	1.204	12.7	12.7
85	0.879	1.261	1.711	1.849	-31.8	31.8
86	1.441	1.927	2.483			
				medians	-10.9	12.7
				means	-13.2	18.3

Table F5. Forecasts, actual catches, and relative errors of forecasts from vector AR(3) models of *first differences* of square root transformed **pink salmon** catches in southern (SSE), northern (NSE) and Southeast (SE) Alaska fishing areas. Catch in numbers/10^7.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.518	1.169	2.080	1.347	-13.2	13.2
82	0.511	1.149	2.043	1.292	-11.0	11.0
83	0.420	1.006	1.843	3.142	-68.0	68.0
84	0.722	1.503	2.568	2.090	-28.1	28.1
85	1.547	2.621	3.977	3.047	-14.0	14.0
86	1.345	2.347	3.626			
				medians	-14.0	14.0
				means	-26.9	26.9
	Northern Southeast Forecast Catch			**Actual Catch**	**Forecast Error**	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.036	0.270	0.722	0.536	-49.6	49.6
82	0.053	0.312	0.788	1.132	-72.4	72.4
83	0.127	0.482	1.064	0.605	-20.3	20.3
84	0.275	0.738	1.425	0.490	50.5	50.5
85	0.281	0.745	1.431	2.050	-63.7	63.7
86	0.333	0.852	1.611			
				median	-49.6	50.5
				means	-31.1	51.3
	Southeast Alaska Forecast Catch			**Actual Catch**	**Forecast Error**	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.765	1.737	3.102	1.897	-8.4	8.4
82	0.452	1.237	2.407	2.425	-49.0	49.0
83	0.829	1.823	3.202	3.750	-51.4	51.4
84	1.200	2.375	3.946	2.582	-8.0	8.0
85	1.644	2.976	4.700	5.099	-41.6	41.6
86	1.901	3.338	5.176			
				medians	-41.6	41.6
				means	-31.7	31.7

Table F6. Forecasts, actual catches, and relative errors of forecasts from vector AR(3) models of *first differences* of square root transformed **chum salmon** catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^6.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.165	0.423	0.800	0.352	20.2	20.2
82	0.230	0.523	0.933	0.840	-37.8	37.8
83	0.192	0.462	0.849	0.514	-10.0	10.0
84	0.507	0.906	1.421	1.831	-50.5	50.5
85	0.609	1.053	1.616	1.301	-19.1	19.1
86	0.978	1.520	2.181			
				medians	-19.1	20.2
				means	-19.4	27.5
	Northern Southeast Forecast Catch			**Actual Catch**	**Forecast Error**	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.415	0.824	1.373	0.487	69.2	69.2
82	0.094	0.325	0.695	0.513	-36.6	36.6
83	0.266	0.605	1.082	0.671	-9.8	9.8
84	1.282	1.938	2.728	2.184	-11.3	11.3
85	1.102	1.711	2.453	1.954	-12.4	12.4
86	0.795	1.316	1.967			
				medians	-11.3	12.4
				means	-0.2	27.9
	Southeast Alaska Forecast Catch			**Actual Catch**	**Forecast Error**	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.428	0.990	1.784	0.850	16.5	16.5
82	0.317	0.812	1.536	1.359	-40.3	40.3
83	0.670	1.339	2.236	1.196	12.0	12.0
84	1.104	1.921	2.963	4.047	-52.5	52.5
85	1.898	2.979	4.303	3.267	-8.8	8.8
86	1.839	2.897	4.193			
				medians	-8.8	16.5
				means	-14.6	26.0

Table F7. Forecasts, actual catches, and relative errors of forecasts from vector AR(3) models of *first differences* of square root transformed **coho salmon** catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^5 except SE is catch in numbers/10^6.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	2.915	5.336	8.484	6.408	-16.7	16.7
82	3.723	6.386	9.763	8.216	-22.3	22.3
83	3.345	5.876	9.114	8.662	-32.2	32.2
84	4.529	7.420	11.021	6.657	11.5	11.5
85	6.269	9.567	13.559	11.984	-20.2	20.2
86	5.092	8.088	11.775			
				medians	-20.2	20.2
				means	-16.0	20.6

	Northern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	2.631	5.308	8.916	6.010	-11.7	11.7
82	2.580	5.212	8.760	10.786	-51.7	51.7
83	4.769	8.277	12.746	10.180	-18.7	18.7
84	6.481	10.465	15.400	10.832	-3.4	3.4
85	6.558	10.517	15.407	11.476	-8.4	8.4
86	7.109	11.169	16.142			
				medians	-11.7	11.7
				means	-18.8	18.8

	Southeast Alaska Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.907	1.399	1.999	1.407	-0.5	0.5
82	0.790	1.248	1.809	2.138	-41.6	41.6
83	1.038	1.568	2.206	1.985	-21.0	21.0
84	1.223	1.793	2.471	1.920	-6.6	6.6
85	1.452	2.065	2.785	2.540	-18.7	18.7
86	1.389	1.985	2.688			
				medians	-18.7	18.7
				means	-17.7	17.7

Table F8. Forecasts, actual catches, and relative errors of forecasts from vector AR(3) models of *first differences* of square root transformed **sockeye salmon** catches in southern (SSE), northern (NSE), and Southeast (SE) Alaska fishing areas. Catch in numbers/10^5 except SE is catch in numbers/10^6.

	Southern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	5.135	7.623	10.601	7.200	5.9	5.9
82	3.969	6.160	8.831	8.421	-26.8	26.8
83	6.280	8.982	12.166	9.437	-4.8	4.8
84	6.128	8.768	11.878	6.476	35.4	35.4
85	4.724	7.070	9.888	11.117	-36.4	36.4
86	8.553	11.696	15.331			
				medians	-4.8	26.8
				means	-5.4	21.9

	Northern Southeast Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.947	2.117	3.752	2.099	0.9	0.9
82	1.084	2.307	3.988	4.389	-47.4	47.4
83	2.732	4.567	6.870	4.723	-3.3	3.3
84	2.682	4.486	6.751	4.548	-1.4	1.4
85	2.767	4.571	6.826	5.040	-9.3	9.3
86	3.255	5.176	7.539			
				medians	-3.3	3.3
				means	-12.1	12.5

	Southeast Alaska Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.668	1.028	1.467	1.080	-4.8	4.8
82	0.702	1.065	1.504	1.493	-28.7	28.7
83	1.066	1.508	2.027	1.569	-3.9	3.9
84	1.010	1.438	1.941	1.204	19.4	19.4
85	0.801	1.184	1.641	1.849	-36.0	36.0
86	1.464	1.980	2.572			
				medians	-4.8	19.4
				means	-10.8	18.5

Table F9. Forecasts, actual catches, and relative errors of forecasts from a vector AR(2) model of square root transformed **pink, coho, and sockeye salmon** catches in southern Southeast Alaska, **and environmental data set A. Catch in numbers: pink/10^7, coho/10^5, and sock/10^5.**

	Pink Salmon Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.291	0.797	1.553	1.347	-40.8	40.8
82	0.845	1.623	2.652	1.292	25.7	25.7
83	0.569	1.221	2.119	3.142	-61.1	61.1
84	1.387	2.372	3.618	2.090	13.5	13.5
85	0.852	1.662	2.739	3.047	-45.5	45.5
86	1.730	2.809	4.148			
				medians	-40.8	40.8
				means	-21.7	37.3

	Coho Salmon Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	3.038	5.674	9.127	6.408	-11.5	11.5
82	5.258	8.567	12.680	8.216	4.3	4.3
83	4.333	7.339	11.132	8.662	-15.3	15.3
84	7.997	11.909	16.598	6.657	78.9	78.9
85	6.033	9.474	13.688	11.984	-20.9	20.9
86	7.460	11.196	15.688			
				medians	-15.3	15.3
				means	7.1	26.2

	Sockeye Salmon Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	4.318	6.667	9.523	7.200	-7.4	7.4
82	4.211	6.508	9.301	8.421	-22.7	22.7
83	4.975	7.442	10.404	9.437	-21.1	21.1
84	3.850	6.042	8.725	6.476	-6.7	6.7
85	5.594	8.185	11.268	11.117	-26.4	26.4
86	6.481	9.351	12.747			
				medians	-21.1	21.1
				means	-16.9	16.9

Table F10. Forecasts, actual catches, and relative errors of forecasts from a vector AR(2) model of *first differences* of square root transformed **pink, coho, and sockeye salmon** catches in southern Southeast Alaska, **and environmental data** set A. Catches in numbers: pink/10^7, coho/10^5, and sock/10^5.

	Pink Salmon Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	0.296	0.691	1.250	1.347	-48.7	48.7
82	0.882	1.510	2.306	1.292	16.9	16.9
83	0.619	1.153	1.853	3.142	-63.3	63.3
84	1.191	1.957	2.913	2.090	-6.4	6.4
85	1.316	2.105	3.079	3.047	-30.9	30.9
86	3.290	4.494	5.886			
				medians	-30.9	30.9
				means	-26.5	33.2

	Coho Salmon Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	2.118	4.343	7.359	6.408	-32.2	32.2
82	5.065	8.283	12.288	8.216	0.8	0.8
83	3.419	6.101	9.554	8.662	-29.6	29.6
84	5.464	8.750	12.805	6.657	31.4	31.4
85	7.312	11.036	15.522	11.984	-7.9	7.9
86	5.670	8.952	12.981			
				medians	-7.9	29.6
				means	-7.5	20.4

	Sockeye Salmon Forecast Catch			Actual Catch	Forecast Error	
yr	Lo 80%	Point	Up 80%		PE	APE
81	4.534	6.927	9.826	7.200	-3.8	3.8
82	4.115	6.381	9.142	8.421	-24.2	24.2
83	5.864	8.521	11.673	9.437	-9.7	9.7
84	6.244	8.952	12.147	6.476	38.2	38.2
85	3.918	6.121	8.812	11.117	-44.9	44.9
86	9.088	12.440	16.316			
				medians	-9.7	24.2
				means	-8.9	24.2

Table F11. Forecasts, actual catches, and relative errors of forecasts from a vector AR(2) model of *first differences* of square root transformed **pink, coho, and sockeye salmon** catches in southern Southeast Alaska, **and environmental data** set B. Catches in numbers: pink/10^7, coho/10^5, and sock/10^5.

yr	Pink Salmon Forecast Catch Lo 80%	Point	Up 80%	Actual Catch	Forecast Error PE	APE
81	0.284	0.828	1.656	1.347	-38.5	38.5
82	0.991	1.882	3.058	1.292	45.7	45.7
83	0.556	1.254	2.232	3.142	-60.1	60.1
84	1.084	2.039	3.294	2.090	-2.4	2.4
85	1.841	3.031	4.517	3.047	-0.5	0.5
86	1.814	2.983	4.440			
				medians	-2.4	38.5
				means	-11.2	29.5

yr	Coho Salmon Forecast Catch Lo 80%	Point	Up 80%	Actual Catch	Forecast Error PE	APE
81	2.104	4.339	7.375	6.408	-32.3	32.2
82	5.353	8.673	12.790	8.216	5.6	5.6
83	3.679	6.467	10.035	8.662	-25.3	25.3
84	5.955	9.376	13.570	6.657	40.8	40.8
85	7.096	10.778	15.227	11.984	-10.1	10.1
86	6.094	9.499	13.657			
				medians	-10.1	25.3
				means	-4.3	22.8

yr	Sockeye Salmon Forecast Catch Lo 80%	Point	Up 80%	Actual Catch	Forecast Error PE	APE
81	4.559	6.959	9.864	7.200	-3.3	3.3
82	4.164	6.441	9.214	8.421	-23.5	23.5
83	5.859	8.515	11.666	9.437	-9.8	9.8
84	6.269	8.982	12.182	6.476	38.7	38.7
85	3.930	6.136	8.830	11.117	-44.8	44.8
86	9.088	12.440	16.316			
				medians	-9.8	23.5
				means	-8.5	24.0